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AN EXPERIMENTAL APPROACH TO THE EFFECTS OF A CHANGE OF SURFACE ROUGHNESS ON THE WIND PROFILE

by

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled, "AN EXPERIMENTAL APPROACH TO THE EFFECT OF A CHANGE OF SURFACE ROUGHNESS ON THE WIND PROFILE", submitted by LORNE A. CAMERON in partial fulfilment of the requirements for the degree of Master of Science.

ABSTRACT

When moving air which is in equilibrium with an underlying surface of a given constant roughness abruptly encounters a surface with a different roughness length a new equilibrium condition is set up gradually. Several theories have been proposed to explain the process of transition under neutral conditions. The author's experimental wind profiles are presented and compared to the theoretical profiles obtained from a modified form of Townsend's theory of self-preserving flow in a turbulent boundary layer. Discrepancies between theory and observation are discussed and suggestions are presented for obtaining definitive results.

AKNOWLEDGEMENTS

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This project was conducted using the facilities of the Defense Research Establishment at Suffield while the author had educational leave from the Meteorological Branch of the Department of Transport.

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INTRODUCTION

The study of the effects of the earth's surface on the atmosphere is of prime importance for future advances in numerical weather prediction. Over a period of 1 or 2 days energy transfer changes between the surface and atmosphere can be neglected but for longer periods such changes must be included. A great deal of work has been done on vertical fluxes of heat, momentum, and moisture, and on the wind profile in the various regimes of stability particularly over uniform terrain. In this paper, I shall consider the effect of a single change of surface roughness on the wind in the surface boundary layer.

Suppose wind has been blowing over a region of uniform roughness length for a long period of time and that the atmosphere is in neutral equilibrium. Then the wind and turbulence will not be changing with x, the downwind distance coordinate, and the wind is said to be in equilibrium with the surface.

Suppose now that the surface abruptly changes to one with an increased roughness length. For example, the wind blows from an extensive flat sandy area to a region of grass. The first effect on the wind is increased friction in the thin layer immediately adjacent to the surface and thus the lowest layer

undergoes a deceleration. The velocity gradient in the vertical increases, and this in turn increases the turbulence. The increased turbulence feeds more momentum into the lower layers to partially overcome the momentum lost. Gradually successively thicker layers of the surface boundary layer are affected, and eventually the wind again will be in equilibrium with the underlying surface, but with a slightly lower mean velocity at any given level and with an increased surface shear stress. Also from the equation of continuity the overall retardation will induce a vertical velocity.

Suppose we measure the velocity profile under conditions of neutral stability just ahead of the surface discontinuity and at several places downstream as in Figure 1.

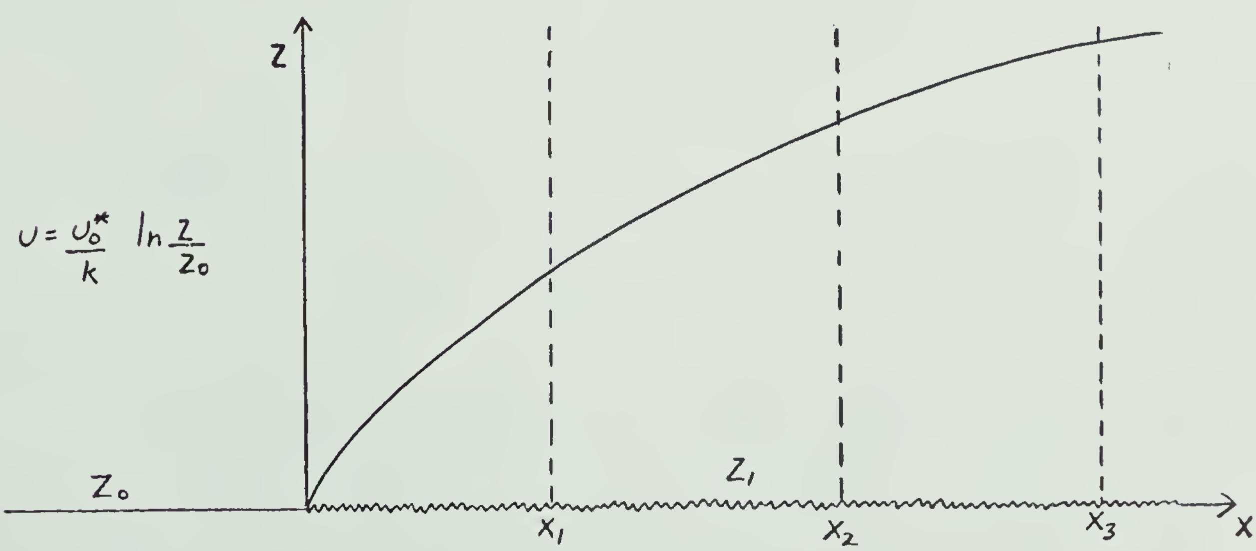


Fig. 1

It would be informative to see what qualitative changes in the profile would occur. It is convenient to graph the profiles with log z against u rather that z against u. Let us assume that the surface roughnesses are z_o and z_1 upstream and downstream, respectively. Because of the assumed stability let us assume that both the original and the new profiles are described by the logarithmic profile (at least in the lowest layer), e.g., $u = \frac{u_o^*}{k} \ln \frac{z}{z_o}$, $x < 0$; $u = \frac{u_1^*}{k} \ln \frac{z}{z_1}$, $x > 0$. Then if $z_1 > z_o$ the following set of profiles might be expected.

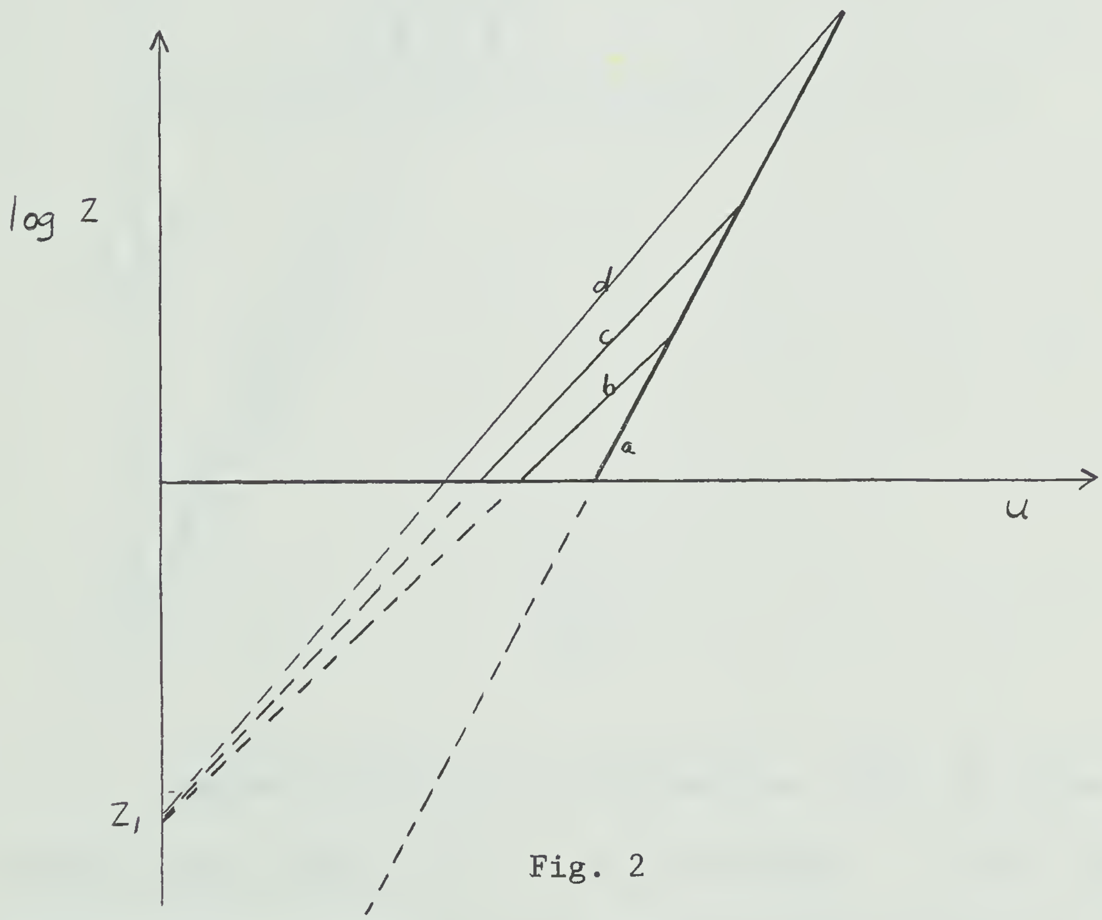


Fig. 2

The original profile is a) and lines b), c), d are the profiles modified farther and farther downstream. The point of intersection of each profile with the original profile serves to

mark the top of the modified layer or internal boundary layer , h . It is observed from experiments that the depth of the internal boundary layer indeed grows with x. If $z_o > z_1$, the following profiles might be expected:

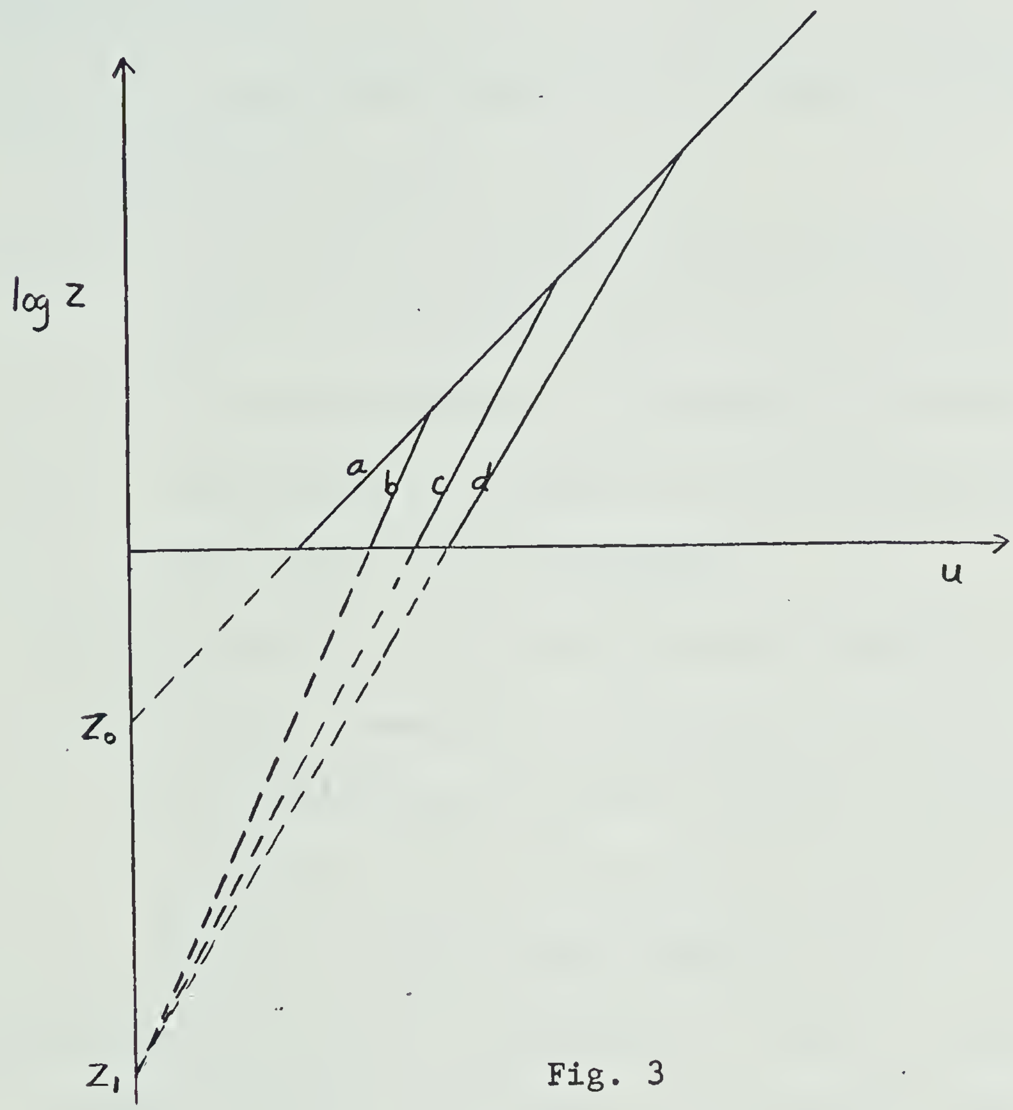


Fig. 3

Friction velocity is defined as $u^{*2} = \frac{\tau_o'}{\rho}$ where τ_o' is surface shear stress and ρ is the density. In this paper the kinematic shear stress will be used. It is defined as $u^{*2} = \tau_o$.

The friction velocity is a function of x. On the graphs the slope $m = \frac{k}{u^*}$. In other words the friction velocity and therefore the square root of the surface stress is inversely

proportional to the slope. The constant k is approximately equal to 0.4 and is called Von Kármán's constant.

Now certain qualitative conclusions can be drawn and questions asked:

(1) The boundary layer grows with x. What is the functional relationship between h and x?

(2) (a) In the case of a smooth surface changing to a rough surface the friction velocity is at a maximum close to the discontinuity and gradually approaches a new equilibrium value greater than the original value but much smaller than the maximum.

(b) In the case of a rough-to-smooth transition the friction velocity is at a minimum immediately behind the discontinuity and then gradually approaches a new equilibrium value less than the original value. How does the surface stress vary with x?

(3) This simple model is unrealistic in that the shear stress is assumed constant with height in the modified layer. It must vary smoothly from the surface value τ_1 to the value at the top of the layer which is τ_o. What will be the shape of the velocity profiles allowing for the smooth vertical variation of stress? Will a simple linear variation of stress with height account for the shape of the velocity profile or is a more involved relationship required?

The following theories will be examined in Chapter I: those of Elliott (1958), Taylor (1962), Panofsky and Townsend (1965), a modification to Townsend's work by Blom and Wartena (1969) and a numerical model by Smith (1967). Chapter II will deal with my experimental results and Chapter III will offer suggestions for future experiments.

CHAPTER I

One of the first theoretical studies of the effects of a change in roughness was made by William P. Elliott in 1958. He assumed, as have subsequent workers, an atmosphere in neutral equilibrium. Then he assumed that, downwind from the change in roughness, the lowest layer was in equilibrium with the new surface up to a height $h(x)$ and was characterized by the logarithmic wind profile. This layer was called the internal boundary layer. Above the internal boundary layer it was assumed that the air was as yet unaffected by the change in roughness. Elliott employed Von Kármán's integral theorem to get an expression for h. He assumed logarithmic wind profiles for u in the internal boundary layer.

The chief difficulty encountered with this approach, besides the clumsy solution, is the implied discontinuity in stress at the boundary surface $z = h$.

In order to overcome Elliott's unrealistic discontinuity of stress at the interface, Panofsky and Townsend used a log-linear velocity profile below the interface

$$u = \frac{u_o^*}{k} \left[(1-s)\ln \frac{z}{z_1} + s \frac{z}{h}\right] \tag{1}$$

where $s = \dfrac{u_o^* - u_1^*}{u_o^*}$ and h is the height of the interface.

This can be rewritten:

$$u = \frac{u_1^*}{k} \ln \frac{z}{z_1} + \frac{1}{k} (u_o^* - u_1^*) \frac{z}{h}$$

where u_o^* represents friction velocity at $x < 0$, and u_1^* represents the friction velocity at $x > 0$. Note that when $z << h$; the distribution approaches the logarithmic one.

Panofsky and Townsend's final result gives h implicitly as a function of x in the following equation:

$$4k^2(\xi - \xi_o) = \eta[\ln \eta - 5 - \frac{1}{2} M + \frac{4 + \frac{7}{6} M - \frac{1}{4} M^2}{\ln \eta - 1 - \frac{1}{4} M} + \frac{4 - \frac{7}{6} M + \frac{1}{24} M^2 - \frac{1}{16} M^3}{(\ln \eta - 1 - \frac{1}{4} M)^2} + \text{terms of order } [\ln \eta - 1 - \frac{1}{4} M]^{-3}] . \tag{2}$$

where $\xi = x/z_o$, $\eta = h/z_o$, $M = \ln z_o/z_1$. The two profiles are very similar. Differences result from the assumed linear variation of stress from the surface to the top of the boundary layer which leads to:

(a) no discontinuity of the velocity gradient

(b) no discontinuity of the shear stress

(c) the resulting height of the boundary layer is greater (mainly because of a change in definition of the location

of the upper surface).

In 1965 Townsend published two important papers dealing with the surface boundary layer and employing the ideas of similarity theory. His first paper (Townsend 1965a) developed the fundamental concepts of self-preserving flow while in his second paper (1965b) he applied these ideas to particular special cases such as flow over a hedge, flow over a fence and flow across a change in roughness. He examined the effects on the temperature and moisture profiles as well as on the velocity profile. It was shown that changes in the flow such as those caused by a change in roughness are substantially independent of any special assumption about the interaction between turbulence and the mean flow.

Self-preserving flow implies that lateral distributions of various quantities have the same form at all distances from the origin, differing only in common scales of velocity and length. In the cases considered by Townsend it was assumed that the deviation of a flow quantity from its value in the undisturbed flow was self preserving. It was shown in his original paper that self-preserving development in the atmospheric boundary layer occurred if:

(1) The velocity defect ratio $|u-u_1|/u_1$ was small except for small z/ℓ_s.

(2) The variation of the roughness with x was small.

(3) $\log \ell_s/z_1$ was large.

The quantity ℓ_s will be defined later.

As in the previous studies Townsend started with a wind blowing from an infinite plain of roughness z_o at $x < 0$ onto a field with roughness length z_1 at $x > 0$. The atmosphere was assumed to be neutral with the wind profile given by $u = \frac{1}{k} \tau_o^{\frac{1}{2}} \ln \frac{z}{z_o}$.

There are two contributions to the modification of the wind profile. One is due to the acceleration of particles of air $V(z)$ and the other is the vertical displacement of the streamlines $\delta(z)$. The profile for $x > 0$ he wrote as:

$$U = U_o + V(z) - \frac{u_o^*}{kz} \delta(z) \qquad (3)$$

where U_o is the original unmodified wind profile.
Near the surface the profile immediately adapted to the new friction velocity. Thus

$$U = \frac{1}{k} (\tau_1(x))^{\frac{1}{2}} \ln \frac{z}{z_1}$$

served as a lower boundary condition.

To find a solution for $V(z)$ Townsend assumed a self-preserving flow of the form

$$V = \frac{u_s}{k} f(\eta) \qquad (4)$$

where $u_s = u_s(x)$ is a velocity scale, $\eta = z/\ell_s$, $\ell_s = \ell_s(x)$ is a length scale, and $f(\eta)$ is a universal function.

The shear stress was also assumed to be self-preserving and of the form:

$$\tau = u_o^{*2} + \tau_s F(\eta) \tag{5}$$

where $\tau_s = \tau_1 - u_o^{*2}$ and $F(\eta)$ is another universal function. Taking the equation of motion

$$U \frac{\partial U}{\partial x} + W \frac{\partial U}{\partial z} = \frac{\partial \tau}{\partial z}$$

and substituting equation (3) and (4) he obtained

$$- \eta \left(\frac{df}{d\eta}\right) = \frac{dF}{d\eta} \; . \tag{6}$$

To obtain an explicit form for $F(\eta)$ and $f(\eta)$ it was necessary to make an assumption regarding the interaction of the mean flow and turbulence. Townsend used the mixing-length momentum transfer relation

$$\frac{dU}{dz} = \frac{\tau^{\frac{1}{2}}}{kz}$$

which led to

$$\frac{df}{d\eta} = \frac{F}{\eta} . \tag{7}$$

Combining (6) and (7) yielded the results:

$$F(\eta) = e^{-\eta}; \quad f(\eta) = -\int_{\eta}^{\infty} \frac{e^{-x}}{x} dx. \tag{8}$$

Townsend determined the velocity and length scales u_s and ℓ_s using the lower boundary condition together with the universal functions $f(\eta)$ and $F(\eta)$. He arrived finally at the result

$$U = U_o - \frac{u_s}{k} [\int_{\eta}^{\infty} \frac{e^{-x}}{x} dx(1+P_1) + P_1(1-e^{-\eta})\eta^{-1}] \tag{9}$$

where

$$P_1 = [\ln \ell_s/z_o - C_o]^{-1}$$

$$\ell_s[\ln \ell_s/z_1 - M - 1] = 2k^2x$$

$$M = \ln z_o/z_1$$

$$u_s = - Mu_o^*\{[\ln \ell_s/z_1 - C][1 + P_1]\}^{-1}.$$

$$C = .577 \qquad C_o = 1.577$$

For the surface shear stress he found

$$\tau_1^{\frac{1}{2}} = u_o^* + u_s(1+P_1) \qquad (10)$$

In summary Townsend showed that flow disturbances caused by a change in roughness are self-preserving if certain conditions are met in the atmosphere. The requirement that the distribution of velocity should be logarithmic near the surface makes the prediction of surface shear stress nearly independent of the exact nature of the turbulent transfer process and the velocity profile is determined within narrow limits by the surface fluxes. To provide an explicit profile, some assumption about the nature of the interaction between the mean flow and turbulence is required in order to derive an expression for $f(\eta)$. Townsend used $f(\eta) = -\int_\eta^\infty e^{-x}/x \, dx$ and showed that Elliott implicity used $f(\eta) = \ln \eta$ for $\eta < 1$ and $f(\eta) = 0$ for $\eta > 1$ while the "Panofsky and Townsend" profile used $f(\eta) = \ln \frac{1}{2}\eta + (1-\frac{\eta}{2})$ for $\eta < 2$ and $f(\eta) = 0$ for $\eta > 2$.

In a recent paper Blom and Wartena (1969) made a slight modification to the work of Townsend. In this paper the authors noted an inconsistency between Townsend's profile and his lower boundary condition. This inconsistency arose because of the first order approximation Townsend used in evaluating the integral $\int_o^\eta V \, d\eta$. He used the approximate solution ηV. This integral arose out of the derivation of an expression between $V(z)$ and $\delta(z)$. Blom and Wartena were able to give an exact expression for the integral using the

functions $F(\eta) = e^{-\eta}$ and $f(\eta) = \int_{\eta}^{\infty} \frac{e^{-x}}{x} dx$ to obtain

$$\int_{o}^{\eta} V d\eta = \frac{u_s}{k} \int_{o}^{\eta} \int_{\eta}^{\infty} \frac{e^{-x}}{x} dx = \frac{u_s}{k} [\eta \int_{\eta}^{\infty} \frac{e^{-x}}{x} dx - 1 + e^{-\eta}]. \quad (11)$$

For small η this gives

$$\int_{o}^{\eta} V d\eta = \eta V - \frac{\eta u_s}{k} . \quad (12)$$

This led to the following expression for the velocity scale:

$$u_s = - M u_o^* (1+P_1)^{-1} [\ln \ell_s / z_1 - C + (1+P_1^{-1})^{-1}]^{-1}. \quad (13)$$

The new velocity scale now allows a domain to exist which satisfies the lower boundary condition.

At the present time the Townsend approach, as modified by Blom and Wartena, is the most physically secure theory available which treats the problem of change in roughness in the neutral atmosphere.

Another interesting solution was developed by Smith (1967). He used the momentum equation

$$(u \frac{\partial u}{\partial x} = \frac{1}{P} \frac{\partial \tau}{\partial z} = \frac{\partial u^{*2}}{\partial z});$$

the momentum flux equation ($u^{*2} = K \frac{\partial u}{\partial z}$, where K is the diffusivity); and an empirical equation for the rate of change of K

$$\left(u \frac{\partial K}{\partial x} = AK \frac{u}{u^*} \frac{\partial u^*}{\partial z} + K \frac{\partial^2 K}{\partial z^2}\right).$$

A is an empirical constant which must be found from experimental data. These three equations were solved numerically with the lower boundary condition $K = 0$ at the ground. The resulting profiles of u and u^* appear realistic, with a new equilibrium regime being established, given sufficient fetch and with a return to the original profile when the roughness returns to its original value.

One advantage of this approach is that the new roughness length can be allowed to vary periodically about a mean value. Smith found that the effective roughness length depended essentially on the period of oscillation and, to a smaller extent, upon its amplitude. The equilibrium value of u^* was found to be a few percent smaller than the corresponding u^* for a constant roughness.

Taylor in 1962 arrived at a different conclusion regarding the variation of surface shear stress with distance. Whereas the other theories predict that the surface stress gradually approaches an equilibrium value far downstream,

Taylor states that the new equilibrium value shoud be achieved almost instantly. Wind tunnel measurements conducted by Taylor tended to support this idea.

In view of the lack of agreement concerning the downwind shear stress future experimental investigations should attempt to determine it accurately.

CHAPTER II

THE SITE

In order to obtain as large a change in surface roughness as possible it was decided to use a water-to-land discontinuity. This would emphasize the effect of roughness and tend to minimize elevation, stability, and possible upwind effects.

The requirements for a suitable location were as follows:

(1) gentle slope away from the water's edge

(2) long fetch over the water

(3) flat land surrounding the lake with long fetches over uniform grass

(4) easy access.

Only one lake was found near Suffield, where the work was carried out, which would satisfy these requirements. It was called Scott's Slough and was located two miles south of the research station.

The land surrounding the lake was very flat to the west and north. To the east and south were gentle rolling hills. The local relief was such that only east, south, and northwest winds could be used. The reasons the other directions were unsuitable were:

(1) Insufficient stretch of uniform grass in many downwind areas,

(2) A wide, soft mud flat on the south shore,

(3) Weeds growing out of the water along the southwest shore,

(4) A large island blocking the east shore,

(5) Part of the south shore rising rapidly away from the water.

DESCRIPTION OF THE EXPERIMENTAL AREA

AREA A

Area A was located on a peninsula and was used when the wind was roughly from 300 degrees. The fetch was approximately 280 meters. The surface consisted of 3 meters of mud, followed by 16 meters of tall (70 cm) fox tail. After the fox tail was another 16 meters of shorter (30 cm) grass before the grass became the short blue prairie grass.

AREAS B AND C

These areas were used with winds from 90 degrees. The fetch was about 300 meters. The surface consisted of 3 meters of mud which changed abruptly to 50-60 cm foxtail that extended for a distance of 30 meters. The next 40-45 meters consisted of shorter (20 cm) denser grass. Point C has a more uniform density and height of grass than point B.

Fig. 4 Scott's Slough

AREAS D AND E

These areas were used with 180 to 230 degree winds. The fetch was 350 meters. The surface was the best, being mud for 4 meters before becoming very tall uniform foxtail for 60 meters at E and 40 meters at D with shorter grass beyond. In all areas the transition from one type of grass to another took place along a very distinct line. The mud flat-to-grass transition was also very abrupt.

INSTRUMENTATION

We used two 8-m masts and one 16-m portable tower permanently mounted on a trailer. The masts were constructed of 2-in. diameter pipe with horizontal supports placed such that the anemometer cups were located 0.5, 1.0, 2.0, 4.0, and 8.0 meters above the ground. The portable tower had been damaged in a high wind so that it was not possible to use it to obtain the 16.0 meter wind except on two early trials. It held the anemometers at the same heights.

The anemometers were Shepherd-Cassella cup anemometers. Their contacts were designed to close momentarily for every 1/720 mile of wind which passed. The anemometers were connected to electric counters with multi-conductor cable.

The usual procedure was to place one mast as close as

practicable to the water on the mud flat. The mud under water was very soft and unsuitable for anchoring a guy rope. As a consequence the mast had to be two or three meters from the water's edge. However there was probably very little change in roughness between the water and the mud compared with the transition from the mud to the grass.

The second mast and the tower were positioned downwind from the first mast. Wind direction was determined by means of a portable wind vane at 2 meters above the ground. It was set up for each trial with a compass. Distances between masts were measured with a surveyor's tape. Air and water temperatures were measured on several days with standard mercury thermometers.

The counters and vehicle were positioned well to one side of the line of towers, (usually more than 25 meters). Every effort was made to minimize disturbance of the grass while setting up towers. Estimates of the fetches were obtained from aerial photographs.

The equipment was easily portable and could be transported to the site and set up by two people in two hours. The procedure followed each day was to obtain the weather forecast in the morning from the Meteorology Section. If the wind was forecast to be from a suitable direction later in the day the towers were set for the forecast wind direction and a test was carried out if the wind cooperated. This procedure

yielded useful data on nine days. The most common reason for failure to obtain more data was the lack of good pressure gradients during much of the summer of 1968. As a consequence the winds were mostly light and variable.

THE DATA

The counters which recorded wind speed were stopped and read every 15 minutes. The total amount of useful data from each trial averaged about 2 hours. The results were divided into two groups. One group consisted of data obtained on sunny days (assumed to be unstable). The other group was obtained under overcast conditions (assumed to be near neutral). On 5 of these occasions the towers were placed at 3, 33, and 63 to 78 meters. An overall mean profile was plotted for these cases (Figure 5). They consisted of 3 unstable cases and 2 neutral cases. Mean profiles were also plotted for the neutral cases (Figure 6) and the unstable cases (Figure 7), separately.

Two trials were conducted with towers located at 3, 13, and 23 meters from the edge of the water. One was neutral and the other was unstable (Figure 8).

From these graphs it is possible to measure the roughness lengths and the friction velocities. Knowing these parameters it is possible to make some comparisons with theory.

The profiles obtained from each trial are plotted on Figs. 14 to 21. The z coordinate is plotted on a logarithmic scale while the velocity u is plotted on a linear scale.

The over-water profiles were drawn as straight lines. It can be seen that not all of the data satisfied the logarithmic "law". Trials 1, 3, 4, 6 and 10 show little deviation from a straight line. However the data points in trials 5, 7, and 8 are concave upwards. The profiles at an average distance of 70 meters downstream show either a smooth curve or a straight line in each of the trials. This would indicate that the wind had approached equilibrium with the surface, at least in the lower levels.

The intermediate profiles, taken at an average of 33 meters from the water's edge, show little if any consistent pattern. In four of the trials the velocity at the 0.5 meter level was less on the intermediate profile than in the more downwind profile. All of the intermediate profiles have at least one point which has a higher velocity than the unmodified wind profile. There is no immediate explanation for this strange behavior. Anemometers were interchanged both between trials and during trials in order to eliminate systematic error.

One feature, consistent among the intermediate profiles, was that the lower three points on seven of the eight trials were nearly collinear. It could be said that the layer from the

surface to two meters had adjusted itself to the new surface conditions. The slope of each of the intermediate profiles is seen to lie between the slopes of the unmodified and the downwind profiles. This indicates that the friction velocity decreased downwind from the point of roughness change after reaching a maximum value. The z intercept and thus the roughness length were different for both of the downwind profiles in each trial, except for trials 7 and 8. This difference was expected due to the variation in the types of grass encountered downwind. Therefore one of the conditions required by Townsend's theory to allow self-preserving flow has been violated.

The modified Townsend profile was calculated for each of the mean profiles using the following method. In each of the four cases the mean profile was first plotted. The values of z_o, z_1 and u_o^* as obtained from the graphs were used as the parameters in the Townsend equations. The theoretical profiles were plotted as broken lines on Figs. 5, 6, 7, and 8.

It can be seen that the Townsend theory understimated the degree of modification of the profile in each case. Note that the slope of the theoretical lines runs parallel to that of the actual lines and also that the roughness lengths correspond as would be expected.

In an attempt to explain the discrepancy between the experimental and theoretical profiles the displacement length D was introduced. D can be thought of as a new datum level below which the wind velocity is zero. For a first estimate D was taken to be 25 cm for tall grass. (Calder ; 1949). Then each of the profiles was also plotted for values of D = 30, 20, 15 and 10 cm. For the larger values of D the profiles became concave downwards, while for D = 10 cm there was little difference from the case D = 0. Using the profiles for D = 15 the roughness lengths and friction velocities were measured and these constants were used to calculate the modified Townsend profiles. (Figs. 9,10,11, and 12).

It can be seen that there was improved agreement between

the theoretical and experimental curves in the neutral case (Fig. 10). However, there was worse agreement in the overall mean (Fig. 9) and little difference in the remaining two cases (Figs. 11 and 12).

These results serve to emphasize the importance of using as near neutral stability as possible in future investigations.

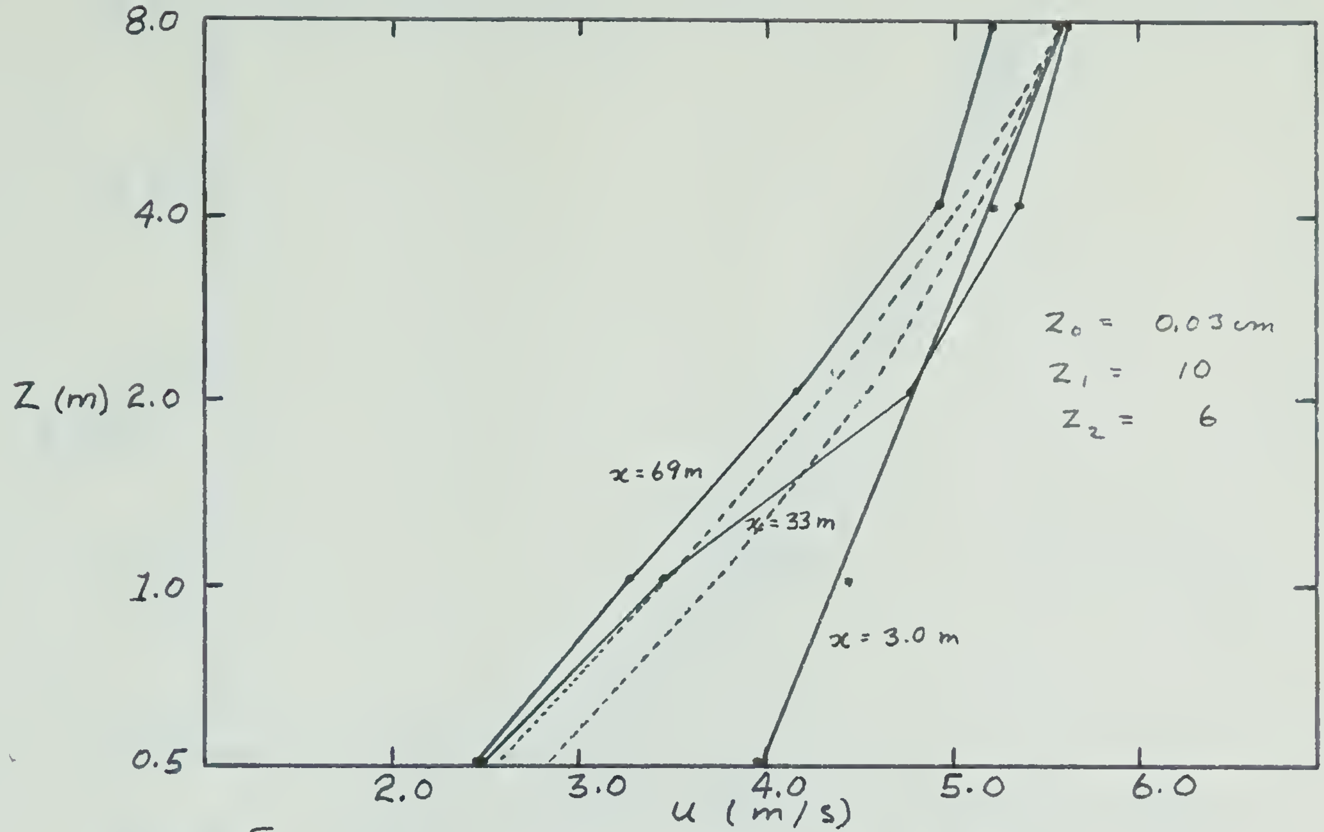


Fig. 5 Mean profile using all data

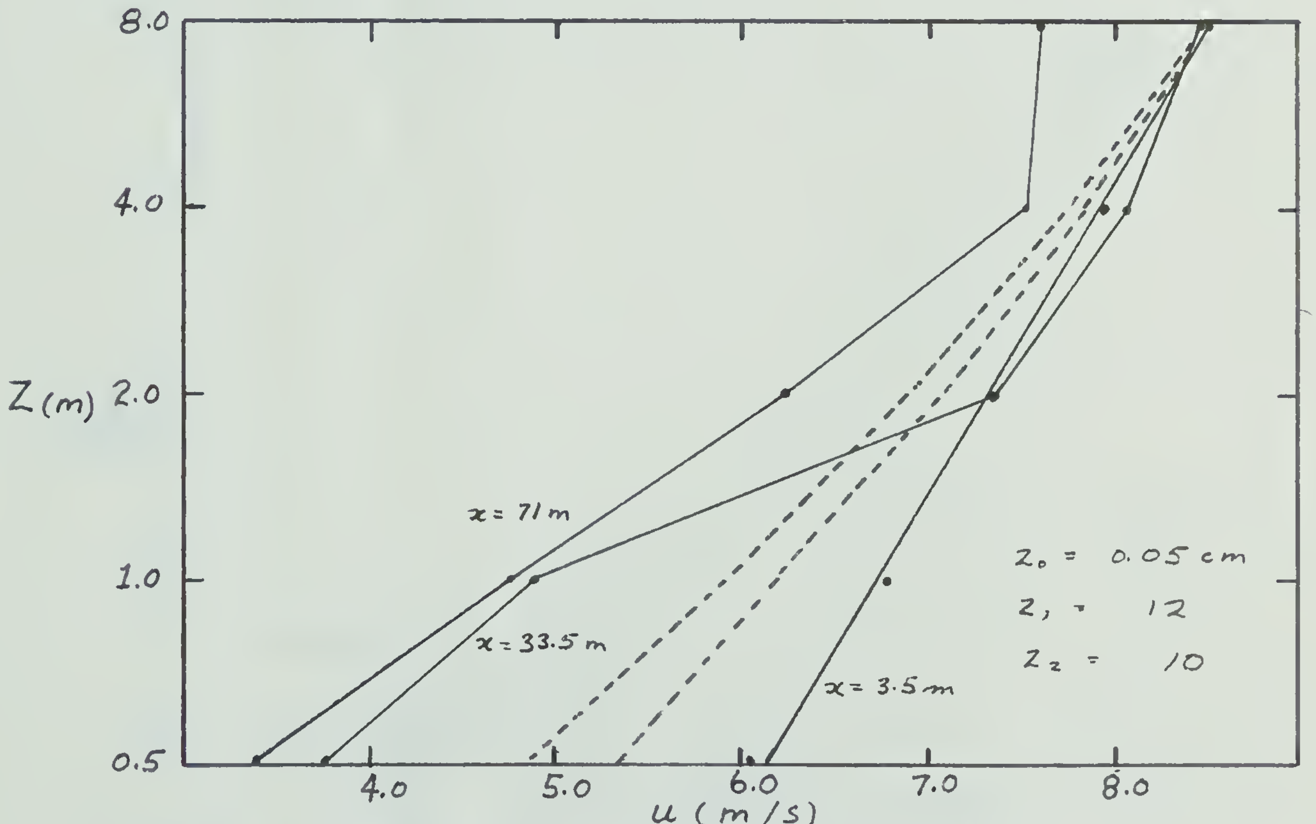


Fig. 6 Mean profile with neutral conditions (trials 5 and 9)

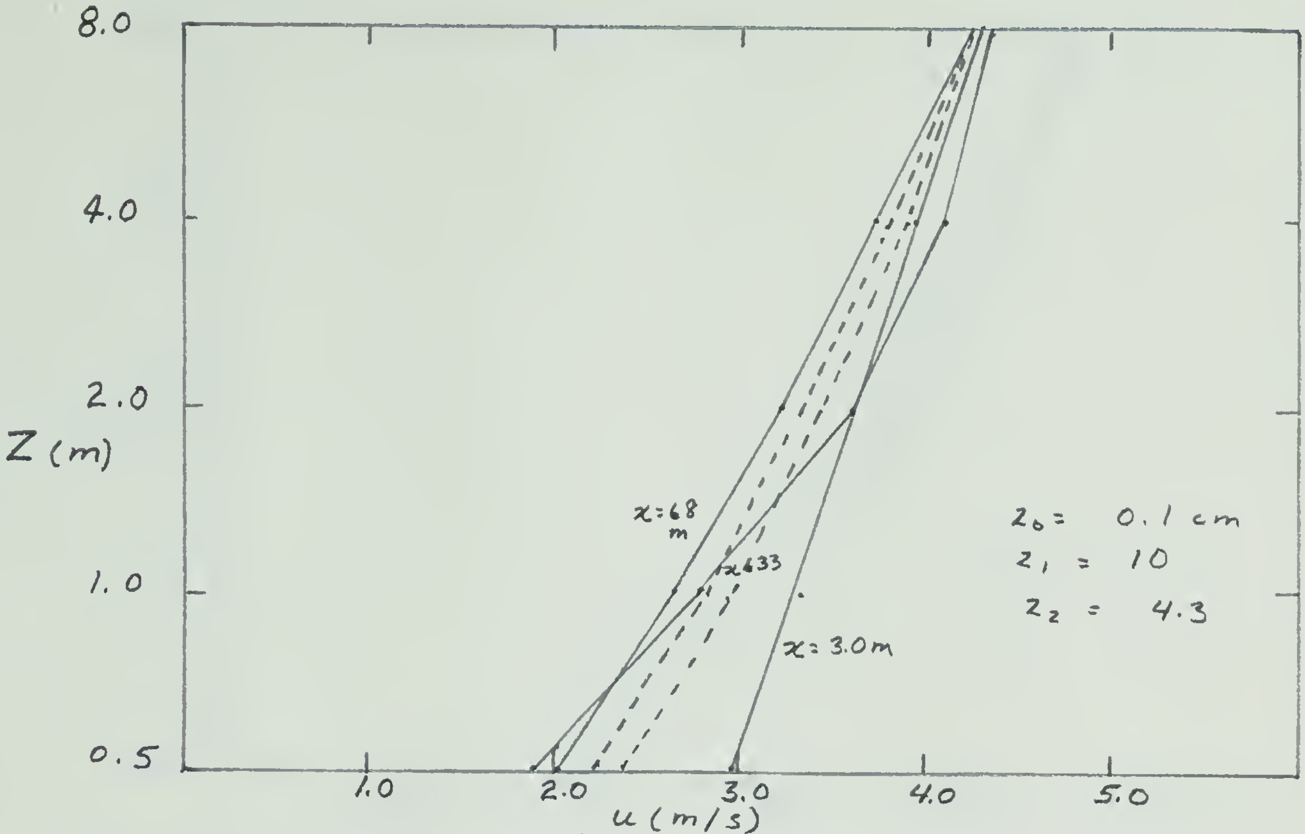


Fig. 7 Mean Profile with Unstable Conditions

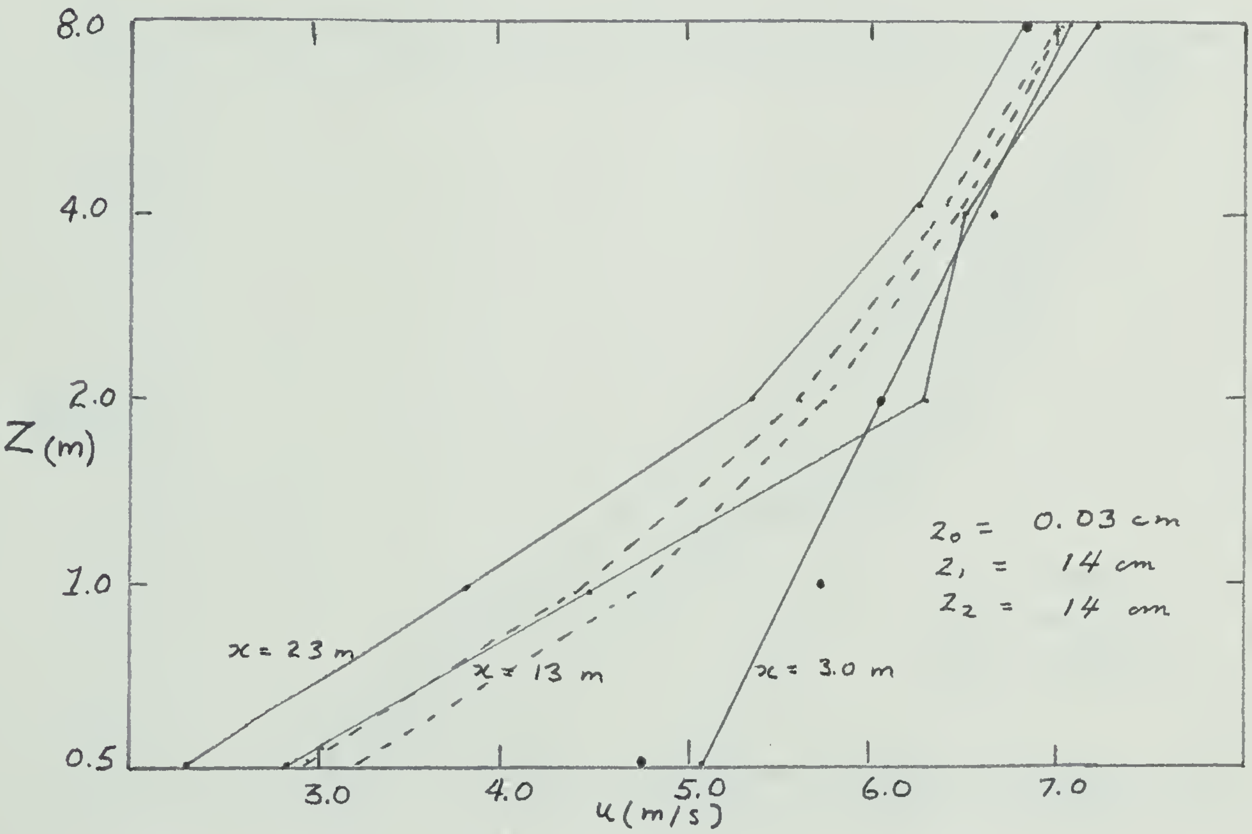


Fig. 8 Mean of Trials 7 and 8

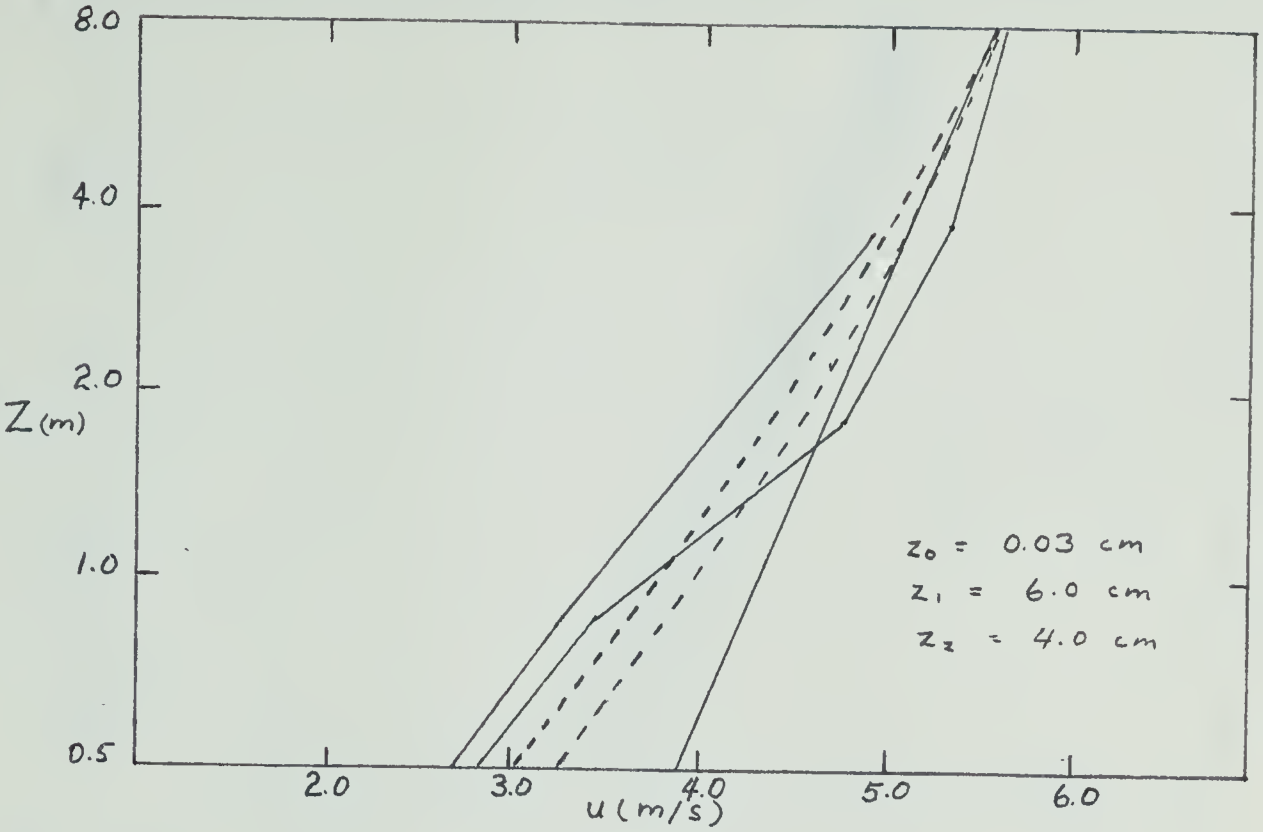


Fig 9. Same as Fig 5 except D = 15 cm

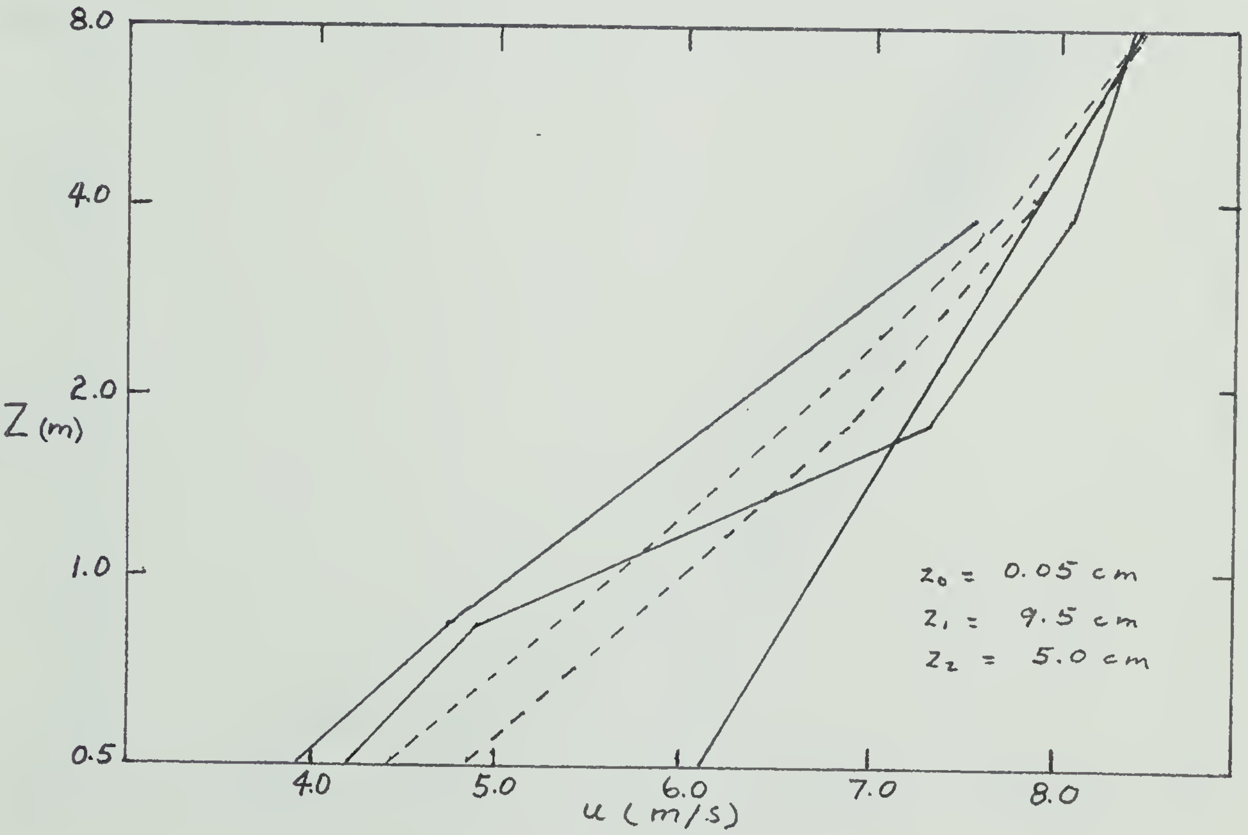


Fig. 10 Same as Fig 6 except D = 15 cm

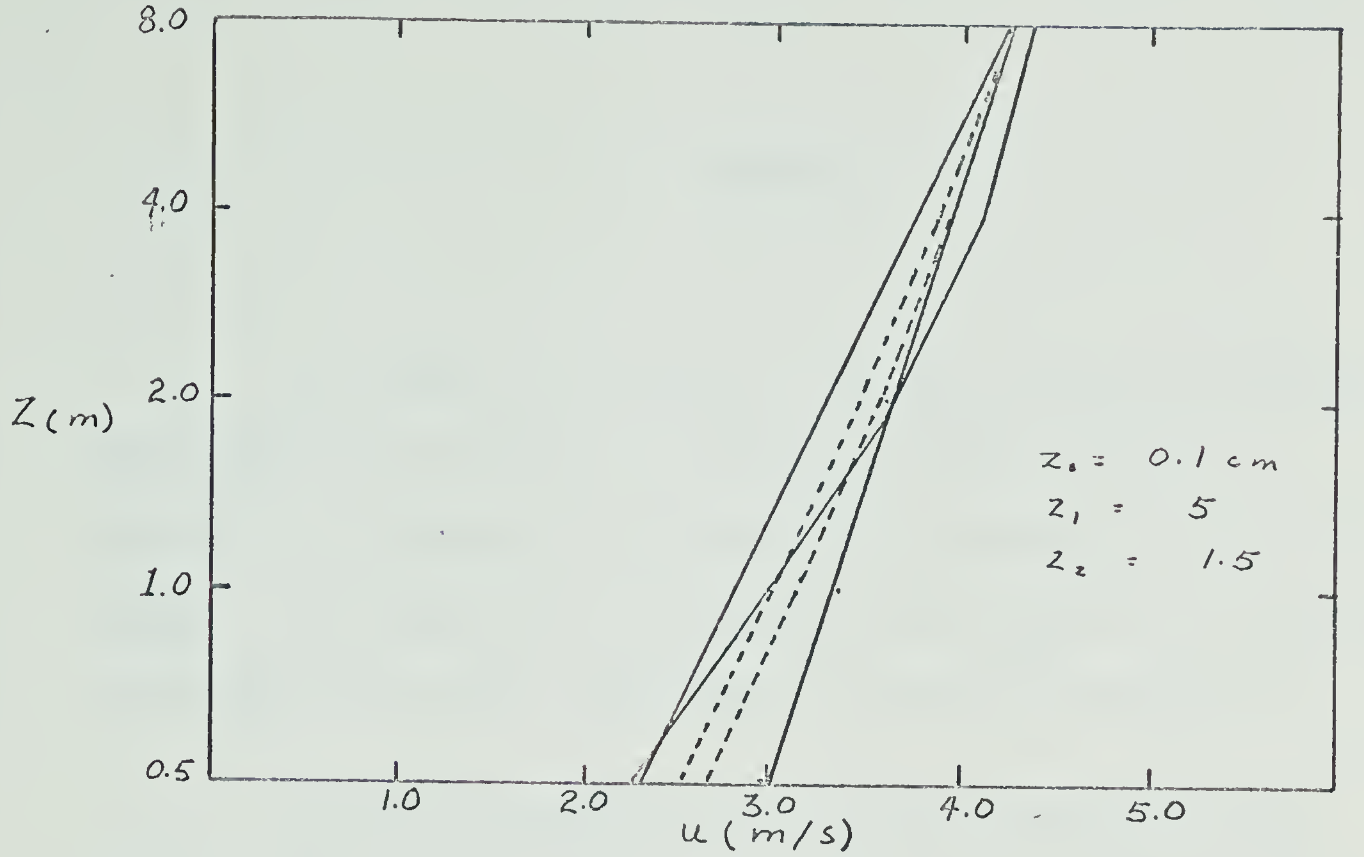


Fig. 11 Same as Fig. 7 except D = 15 cm

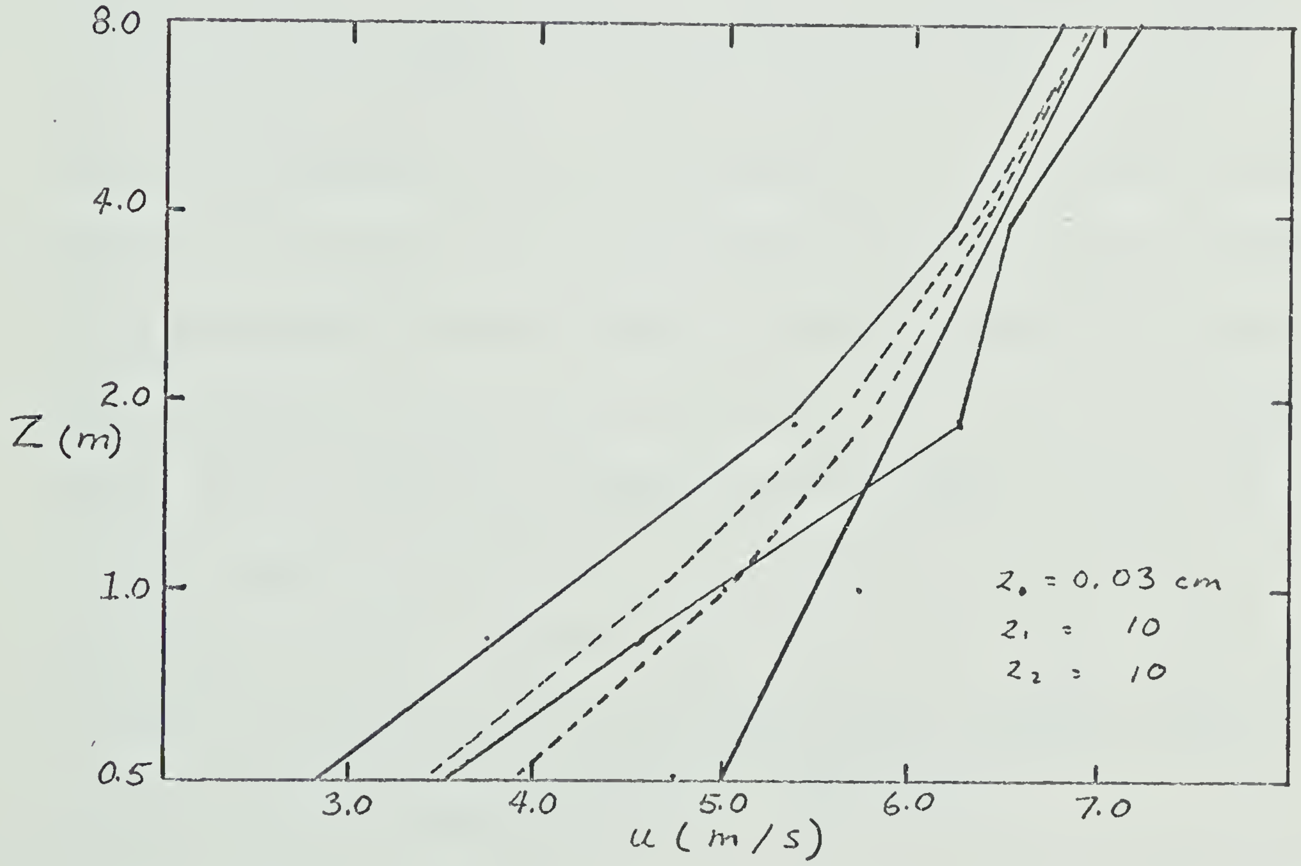


Fig. 12 Same as Fig 8 except D = 15 cm

CHAPTER III

In Chapter I we looked at the models presently available which explain the effects of a change in surface roughness. In Chapter II we discussed and compared our experimental results with theory. This chapter will discuss the shortcomings of the experiment as conducted and offer suggestions for further investigations.

In all the theories that have been published to date certain assumptions have been made which must be recognized when designing an experiment. The most important of these assumptions is that the atmosphere is in neutral equilibrium. Perhaps in the future it will be shown that to a first approximation stability can be ignored. However, at the present time the majority of trials should be undertaken in neutral conditions. The second assumption which has been made is that the wind profile is fully established. In other words the shear stress is assumed constant with height. Thus the second requirement is that there is a very long upwind fetch of the order of a kilometer or more (Blom and Wartena 1969). A third condition which must be met is that a single abrupt change in roughness exists and the surface must be of uniform composition. A fourth condition is that the surface must be nearly level so as to eliminate systematic vertical velocities.

The location of the experiment is the critical point. Several possibilities present themselves. A large body of water can be used as the first surface with a uniform shoreline as the second. The advantage of this layout is that an extremely large discontinuity can exist, the roughness length of calm water being of the order 0.01 cm and that of grass of the order 5 cm. However, there are a number of disadvantages. The first is the difficulty of locating a body of water which fulfills the following requirements. The shore must slope away from the water line very gently. The shore must be of uniform composition away from the water for a distance of 100 meters at least. The fetch across the water should be of the order of a kilometer. The second disadvantage is the difficulty encountered in making measurements of wind and temperature over the water.

The shortcomings mentioned above are easily circumvented by using a land-to-land change of surface roughness. At Suffield the obvious choice for the upwind uniform surface is the natural prairie grass which grows uniformly for tens of miles. Several possibilities present themselves for the choice of the second surface. The first that comes to mind is to use the runways at the airport.

The advantages of using runways are manifold. First they are convenient and accessible. Electric power is nearby for the instruments if needed. The orientation of the runways is in the direction of the prevailing winds. The airport receives

little traffic so that there would be little inconvenience. In the event of rain the experiment won't be bogged down in mud. There is no danger of the surface being trampled by people or vehicles travelling on it as in the case of deep grass. The major disadvantage of the use of a runway is that the wind must blow exactly parallel to it in order to avoid lateral boundary effects.

The second thought that comes to mind is to artificially modify the prairie grass in order to change its roughness length. Since the grass is naturally short it is doubtfull the roughness length could be modified appreciably by mowing. It would probably be more effective to destroy the grass over a large area by either fire, herbicide, or ploughing. The resulting bare earth would probably have a roughness length appreciably different from that of grass so that the wind would be significantly modified by it. If such a scheme were attempted the best experimental area shape would be either circular or octagonal of radius 75 meters. One major advantage to such a scheme is that trials could be carried out with winds from any direction.

A third method of carrying out the experiment is to use two adjacent cultivated fields. However such an area is unlikely to be found in the vicinity of Suffield where very little agriculture is carried on.

My recommendation for a site therefore is to modify the

prairie grass in a flat region near the station. The quantities which are to be determined are, primarily, surface shear stress and the wind profile and, secondarily, the temperature profile.

In order to make a detailed study of the wind profiles it is necessary to use a large number of levels and several downwind positions. The minimum number of levels I would recommend is six, ranging from 1/4 meter to 8 meters for the first four positions; say at 10, 20, 40 and 80 meters from the change in roughness and from 0.5 to 16 meters for downstream distances beyond 80 meters.

There will be certain technical difficulties associated with such a number of towers, so widely spaced. The first is in procuring the required materiel; four 8-meter towers, two 16-meter towers, thirty-six anemometers and counters. Also there would be the sheer physical problem of aligning the towers with the direction of the wind. It was our experience that two men required at least two hours to set up 3 towers and to test the anemometers. Another major problem which needs to be overcome is that of recording all the data simultaneously. To connect all anemometers by cable to a central point would require close to 500 meters of 7 — conductor cable; (or 13 — conductor cable if temperature measurements are also made).

These problems are such that it would be mandatory to set the towers up permanently and then wait for the wind to blow in the

chosen direction. In order to overcome these difficulties without losing resolution, a single highly portable tower could be employed like a probe in a wind tunnel. It could be mounted on the rear of a half ton truck, together with the counters, and be moved from point to point downwind.

It is necessary to assume a steady state wind when using a moveable tower. This condition is satisfied to a high degree whenever the geostrophic wind is relatively strong.

The experimental technique would be as follows. One tower would be set up ahead of the roughness change and to one side. Ideally it would be a 16 meter tower but an 8 meter tower would suffice. One man would be required to record the readings on counters every 15 minutes. The moveable probe would be positioned first at 10 meters away from the line of change and a ten minute mean profile obtained. These profiles might be taken at 10, 20, 40, 80 or any desired interval depending upon what type of cross-section is desired.

Since the equipment is highly portable it is necessary to be able to measure distances accurately and quickly. A suggestion would be to count the number of revolutions of the wheels of the truck, and knowing their circumference to calculate the distance travelled. The most practical way to count wheel revolutions is to use the truck's speedometer cable. A cam on the cable can be used to actuate a microswitch. A standard electric counter can

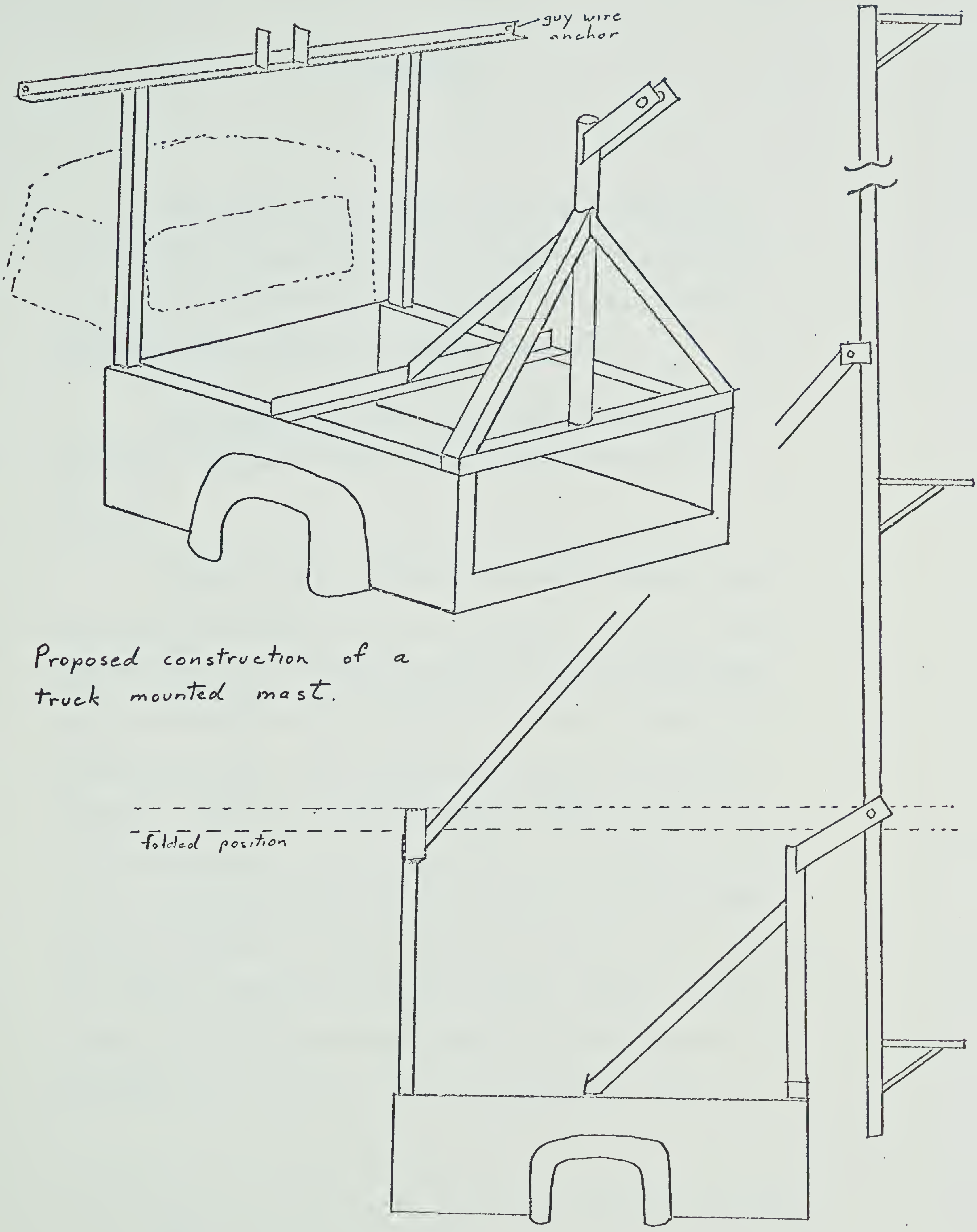
then be used. Normally the cable makes 1000 revolutions per mile or 1 revolution per 5.28 feet.

A tower or mast should be attached to the rear of a pickup truck in such a way as to allow it to be lowered for travelling and for making adjustments to the instruments. A practical method of building the tower on a truck is shown in Figure 13 . The mast should be constructed of two-inch steel tubing. Anemometer supports would be welded in place so as to place the cups at 8.0, 4.0 and 2.0 meters.

A frame constructed of angle iron is bolted to the rear of the truck and places the mast pivot slightly above the level of the cab. Two guy wires are attached to the sides of the body of the truck. To eliminate the need for a third rope to the ground, an aluminum pole of 2 inch diameter is used. It is bolted to a bracket welded to the mast at roughly the six meter level and is carried in a socket on the rear edge of the cab.

The anemometers for the 2.0, 1.0, 0.5 and 0.25 levels are mounted on a separate stand constructed of water pipe. This allows the stand to be located several meters to one side of the truck. The lower level instruments therefore will be outside the area where the wind would be disturbed by the presence of the truck.

The following sketches will indicate a possible method of constructing the apparatus: (Fig. 13)



Proposed construction of a truck mounted mast.

Fig 13

SUMMARY

The object of this project was to find experimental confirmation of one of the theories describing the changes in wind profile and associated parameters to a change in surface roughness under conditions of neutral stability.

For a number of reasons which have been discussed previously, the desired quantitative results could not be achieved.

However, a few qualitative conclusions could be drawn from visual examination of the wind profiles. First the lowest layer of air (0 - 1.0 meter) appears to come to equilibrium with a new surface very quickly and is closely described by the logarithmic profile, thus supporting one of the assumptions of Townsend. Second the friction velocity changes abruptly at or close to the point of change of roughness. It appears to return to a new equilibrium value far downstream. Third for one case which was assumed to be under conditions of near neutral stability the Townsend profile fits the data closely. However, the lack of accurate stability measurements prevents any firm conclusions to be drawn.

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APPENDIX A

(Elliott 1958)

THE ELLIOTT PROFILE

The problem Elliott undertook to solve was to compute the height of the internal boundary layer as a function of downwind distance x. First he considered a region bounded by the top of the boundary layer, the ground and two vertical lines a distance x apart. The loss of momentum out of the region by convection according to the Von Kármán integral theorem is given by

$$\left\{\frac{d}{dx}\int_{z_o}^{h} \rho u^2 dz - u_h \frac{d}{dx}\int_{z_o}^{h} \rho u dz\right\}\delta x. \qquad \text{(A1)}$$

Assuming conservation of momentum this expression must equal the net gain of momentum due to vertical flux into the region. The vertical momentum flux is equal to the difference in shearing stress between the top and the bottom of the layer. Thus

$$\frac{d}{dx}\int_{z_o}^{h} \rho u^2 dz - u_h \frac{d}{dx}\int_{z_o}^{h} \rho u dz = \tau_h - \tau_o \ . \qquad \text{(A2)}$$

This equation can now be used to determine h if the variation of wind speed with height is known.

Elliott assumed a neutral atmosphere with $u' = \frac{u'_*}{k} \ln z/z'_o$ in the undisturbed region upwind of and above the disturbed area. The wind profile in the internal boundary layer was assumed to be $u = \frac{u_*}{k} \ln z/z_o$. When these profiles are used it is implied that u'_* is constant, because of equilibrium conditions upstream, and that u_* is a function of x but not of z. Therefore, at the top of the boundary layer there will be a discontinuity in the stress and in the velocity gradient. With these assumptions equation (A2) was written as:

$$\frac{d}{dx} \int_{z_o}^{h} u^2 dz - u_h \frac{d}{dx} \int_{z_o}^{h} u dz = u'^2_* - u^2_* . \qquad \text{(A3)}$$

The full solution of (A3) was derived by Elliott in his Ph.D. dissertation in 1958. He obtained the following differential equation:

$$\{\ln Z_1 - 3 - \frac{1}{Z_1} + \frac{4}{\ln Z_1} (1 - \frac{1}{Z_1})\} \frac{dZ_1}{dx} = (1 + \frac{\ln Z_1}{\ln mZ_1}) \frac{k^2}{z_o} \qquad \text{(A4)}$$

where $Z_1 = h/z_o$, $m = z_o/z'_o$.

Integrating (A4) results in

$$2kX = Z_1 \ln Z_1 - 4Z_1 - \ln Z_1 + 4 \sum_{n=1}^{\infty} \frac{(\ln Z_1)^n}{n \cdot n!}$$

$$+ \ln c\{\frac{\ln(\ln cZ_1)}{c} (\ln Z_1 - 3 - 2c)$$

$$+ \frac{1}{c} \sum_{n=1}^{\infty} \frac{(\ln cZ_1)^n}{n \cdot n!} (\ln Z_1 - 3)\}$$

$$+ 4(\ln \ln cZ_1)(1 - \frac{1}{c}) + 4\{ \sum_{n=1}^{\infty} \frac{(\ln Z_1)^n}{n \cdot n!}$$

$$- \frac{1}{c} \sum_{n=1}^{\infty} \frac{(\ln cZ_1)^n}{n \cdot n!}\} + \text{constant.}$$

The constant c was determined by the condition that $h = z_o$ at $x = 0$ which may not be true in practice. From dimensional arguments Elliott derived an approximation to his solution:

$$\left(\frac{h}{z_o}\right)\left(\ln \frac{h}{z_o}\right)^{1/5} \propto X^{1/5}. \qquad \text{(A5)}$$

APPENDIX B

(Panofsky and Townsend 1964)

PANOFSKY AND TOWNSEND PROFILE

This theory is an extension of the Elliott theory and differs in only one detail. Whereas Elliott assumed a logarithmic profile in the disturbed region, Panofsky and Townsend used a log-linear profile.

$$u = \frac{u_1^*}{k}\left[(1-s)\ln\frac{z}{z_o} + s\,\frac{z}{d}\right] \tag{B1}$$

where $s = (u_1^* - u_o^*)/u_1^*$.

The profile follows from the mixing length relation $\frac{\partial u}{\partial z} = \frac{u^*}{kz}$ with

$$u^* = u_1^*\left[(1-s) + s\,\frac{z}{d}\right] = u_o^* + (u_1^* - u_o^*)\frac{z}{d}$$

from which it can be seen that the friction velocity is a linear function of height with the value $u^* = u_o^*$ at $z/d = 0$ and $u^* = u_1^*$ at $z/d = 1$. Choose a streamline at a level z_1 well upstream from the discontinuity. Then the volume of air per unit time passing a vertical plane is

$$\int_{z_o'}^{z_1} u\,dz = z_1[\ln(z_1/z_o') - 1]. \tag{B2}$$

The height of the same streamline at the boundary is d and the volume of air is

$$\int_{z_o}^{d} u\,dz = [(1-s)(\ln(d/z_o) - 1) + s/2]d \qquad \text{(B3)}$$

Assuming steady and incompressible flow these expressions are equal. Since the velocity must be continuous across the interface

$$(1-s)\ln(d/z_o) + s = \ln z_1/z_o' \,. \qquad \text{(B4)}$$

Eliminating z_1

$$s(\ln(d/z_o)-1) = \ln z_o'/z_o - \ln\left[\frac{1 - (\ln(d/z_o)(1-\frac{\frac{1}{2}s}{1-s}))^{-1}}{1-(\ln(d/z_o))^{-1}}\right] \qquad \text{(B5)}$$

in which the last term is negligible in most cases. The approximation

$$s = \frac{\ln z_o'/z_o}{\ln(d/z_o)-1} \qquad \text{(B6)}$$

is sufficiently accurate and implies that there is no displacement of the streamlines caused by the discontinuity in roughness.

Conservation of momentum in the whole flow is imposed by the integral constraint:

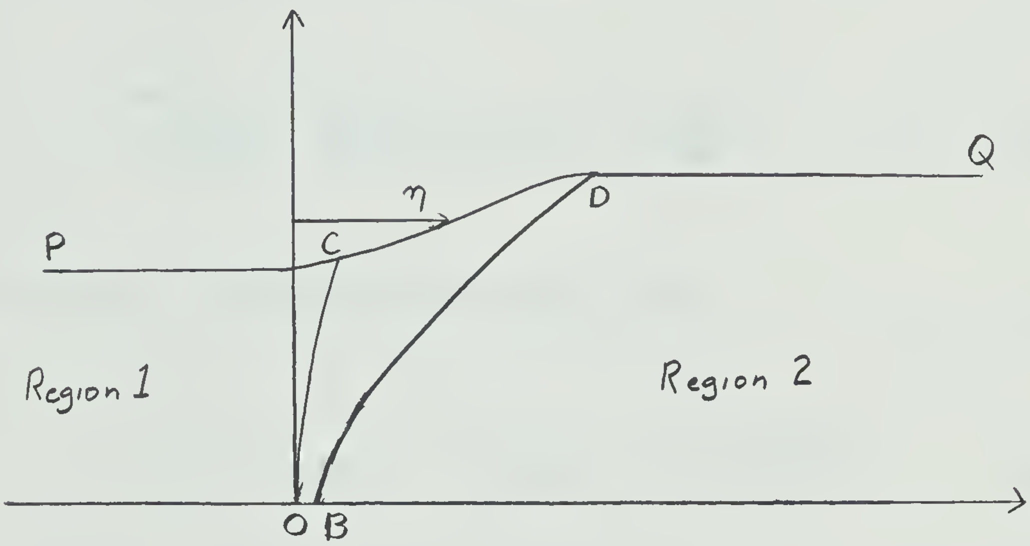
$$\int_{o}^{d} \left(u\frac{\partial u}{\partial x} + w\frac{\partial u}{\partial z}\right)dz = u_1^{*2} - u_o^{*2} = u_1^{*2}s(2-s) \qquad \text{(B7)}$$

APPENDIX C

(Taylor 1962)

THE TAYLOR THEORY

Taylor considered the situation as sketched below:



A fully extablished profile in Region 1 encounters an increased roughness at the origin, point O. In Region 2, a new profile with constant shearing stress is established. The region OBDC is the region of transition with OC and BD as lines of constant stress. The line PQ represents a typical streamline. The length between the origin and a point midway in the transition region is called η . Taylor derived an expression for η as a function of z.

Taylor's starting point was the equation of motion:

$$u \frac{\partial u}{\partial x} + w \frac{\partial u}{\partial z} = \frac{\partial}{\partial z} u_*^2 - \frac{1}{\rho} \frac{\partial p}{\partial x} . \qquad (C1)$$

Defining a stream function ϕ , with

$$\frac{\partial \phi_1}{\partial z} = u, \quad \frac{\partial \phi_1}{\partial x} = - w , \tag{C2}$$

he rewrote the equation of motion

$$\frac{\partial \phi_1}{\partial z}\frac{\partial u}{\partial x} - \frac{\partial \phi_1}{\partial x}\frac{\partial u}{\partial z} = \frac{\partial}{\partial z} u_*^2 - \frac{1}{\rho}\frac{\partial p}{\partial x} . \tag{C3}$$

Integration over the transition region gave:

$$\int_o^{\phi} (u''-u')d\phi_1 = - \oint u_*^2 dx - \rho^{-1} \oint p\, dz \tag{C4}$$

$$= - X - Y .$$

Single and double primes represent quantities in Regions 1 and 2 respectively. ϕ is the value of the stream function along CD. The velocity difference $(u'' - u')$ is measured along a streamline. The line integrals are taken in the direction OBDC. X was shown to be:

$$\eta(u_*'^2 - u_*''^2)$$

and Y was shown to be small compared with X. The stream function for wind in neutral conditions was shown to be:

$$\phi = \frac{u_* z}{k}\{\ln(z/z_o) - 1\} \tag{C5}$$

for $z/z_o >> 1$ and

$$\int_o^{\phi} u d\phi_1 = zu^2 - 2\phi u_* k^{-1} . \tag{C6}$$

It is now possible to calculate η given u_*', u_*'', z_o' and z_o'' using equations (C4), (C5) and (C6) without performing any integrations.

By means of dimensional analysis and by an examination of the available data, Taylor came to the conclusion that the ratio of the new friction velocity to the old was equal to the ratio of the roughness lengths raised to the 0.09 power. From wind tunnel experiments he concluded that the friction velocity was constant downwind from the change of roughness.

APPENDIX D

TRIAL 1

18 July 68

Wind Direction	205°
Orientation of Towers	185°
Cloud Cover	none
Temperature	79°F.
Location	D
Fetch	350 m.
Water Temperature	80°F.

z \ x =	3	33	63
8.0	3.10	3.10	3.04
4.0	2.90	2.97	2.86
2.0	2.71	2.67	2.36
1.0	2.55	2.17	1.93
0.5	2.09	1.51	1.51

(x and z measured in meters; other numbers are velocity in m/sec.)

TRIAL 2

31 July

Wind Direction	215°
Orientation of Towers	220°
Cloud Cover	none
Temperature	70°F.
Location	D
Fetch	350m.
Water Temperature	70°F.

z \ x =	0	6	16
8.0		5.85	6.26
4.0		5.83	5.75
2.0	5.34	5.60	5.44
1.0		5.26	4.31
0.5	4.61	3.10	2.35

TRIAL 3

12 August

Wind Direction	330°
Orientation of Towers	310°
Cloud Cover	100%
Temperature	63°F.
Location	A
Fetch	280m.
Water Temperature	66°F.

z \ x =	3	19	35
8.0	7.52	7.39	7.35
4.0	7.07	7.15	6.86
2.0	6.28	6.56	5.93
1.0	5.52	5.37	4.60
0.5	4.93	3.73	3.35

TRIAL 4

13 August

Wind Direction	100°
Orientation of Towers	90°
Cloud Cover	scattered Cu
Temperature	67°F.
Location	B
Fetch	300m.
Water Temperature	68°F.

z \ x =	3	33	78
8.0	5.73	5.99	5.77
4.0	5.35	5.64	4.86
2.0	5.00	4.89	4.35
1.0	4.43	3.86	3.70
0.5	3.95	2.75	2.92

TRIAL 5

14 August

Wind Direction	90°
Orientation of Towers	90°
Cloud Cover	Overcast, occasional drizzle
Temperature	54°F.
Location	B
Fetch	300m.
Water Temperature	58°F.

z \ x =	3	33	78
8.0	5.69	5.42	5.60
4.0	5.26	5.57	5.12
2.0	4.91	4.72	4.20
1.0	4.43	2.74	3.41
0.5	3.75	2.53	2.83

TRIAL 6

16 August

Wind Direction	90°
Orientation of Towers	90°
Cloud Cover	overcast thin cirrus
Temperature	64°F.
Location	C
Fetch	300m.
Water Temperature	62°F.

z \ x = 3	3	33	63
8.0	3.10	3.21	3.04
4.0	2.97	2.92	2.79
2.0	2.38	2.47	2.39
1.0	2.36	1.83	1.85
0.5	2.22	1.00	1.24

TRIAL 7

18 August

Wind Direction	330°
Orientation of Towers	330°
Cloud Cover	broken Cu
Temperature	64°F.
Location	A
Fetch	280m.
Water Temperature	67°F.

z \ x = 3	3	13	23
8.0	7.33	7.79	7.34
4.0	7.10	6.99	6.79
2.0	6.54	6.71	5.83
1.0	5.97	4.76	4.10
0.5	5.15	3.05	2.38

TRIAL 8

20 August

Wind Direction	90°
Orientation of Towers	90°
Cloud Cover	overcast, light rain
Temperature	63°F.
Location	C
Fetch	300m.
Water Temperature	65°F.

z \ x = 3	3	13	23
8.0	6.31	6.58	6.23
4.0	6.13	6.03	5.66
2.0	5.82	5.83	4.90
1.0	5.42	4.32	3.54
0.5	4.27	2.65	2.10

TRIAL 9

26 August

Wind Direction	210°
Orientation of Towers	190°
Cloud Cover	8/10 As
Temperature	---
Location	E
Fetch	350m.
Water Temperature	---

z \ x =	4	34	64
8.0	10.09	10.39	8.58
4.0	9.63	9.56	8.95
2.0	8.78	9.03	7.44
1.0	8.30	6.42	5.49
0.5	7.54	4.48	3.53

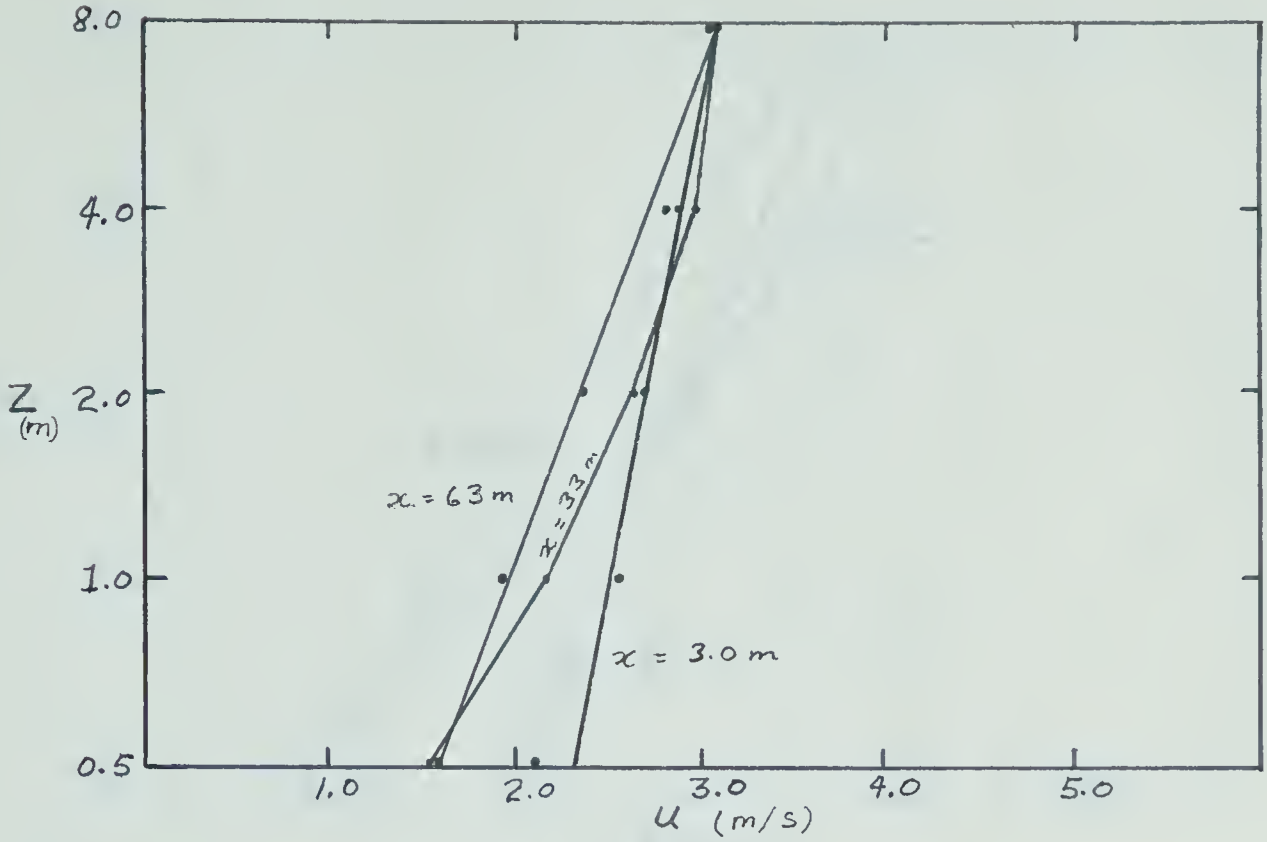


Fig 14 Trial 1

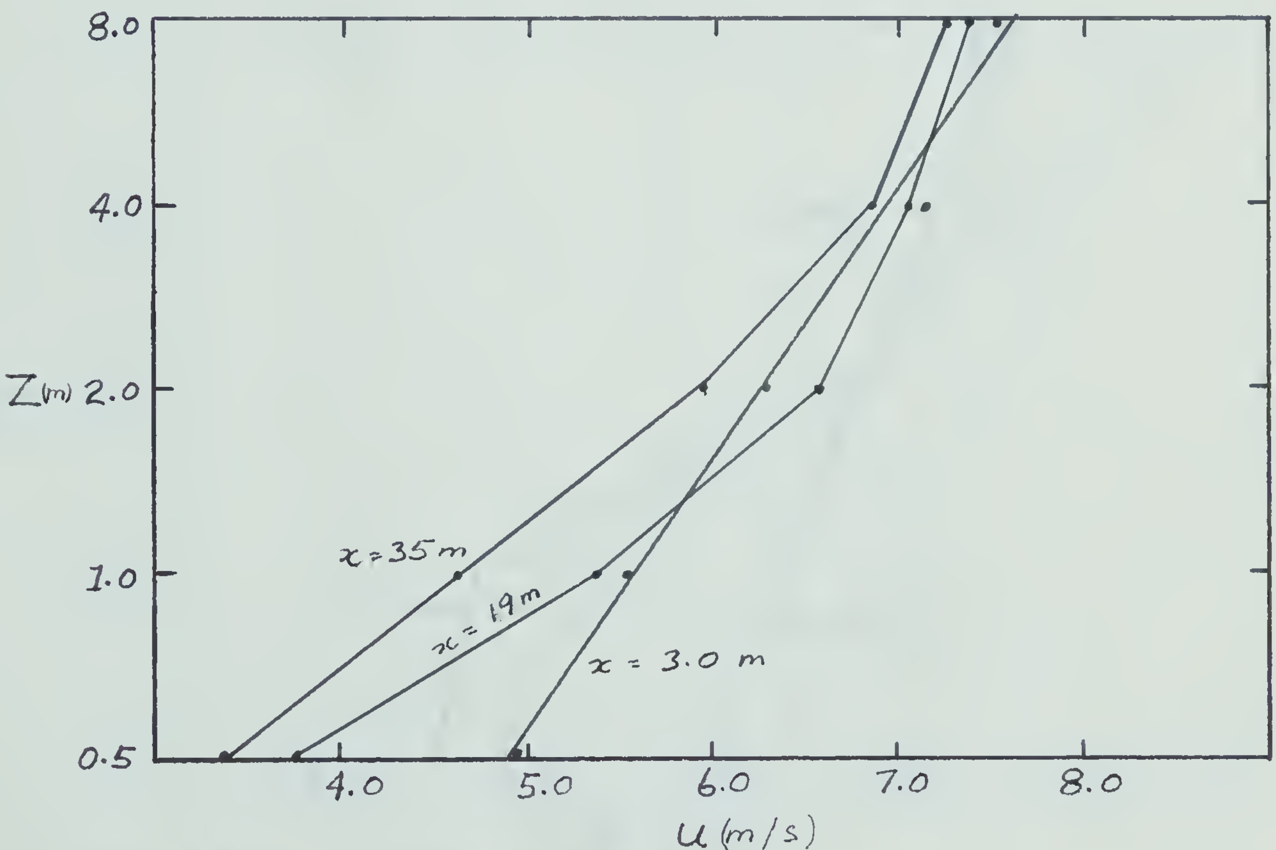


Fig 15 Trial 3

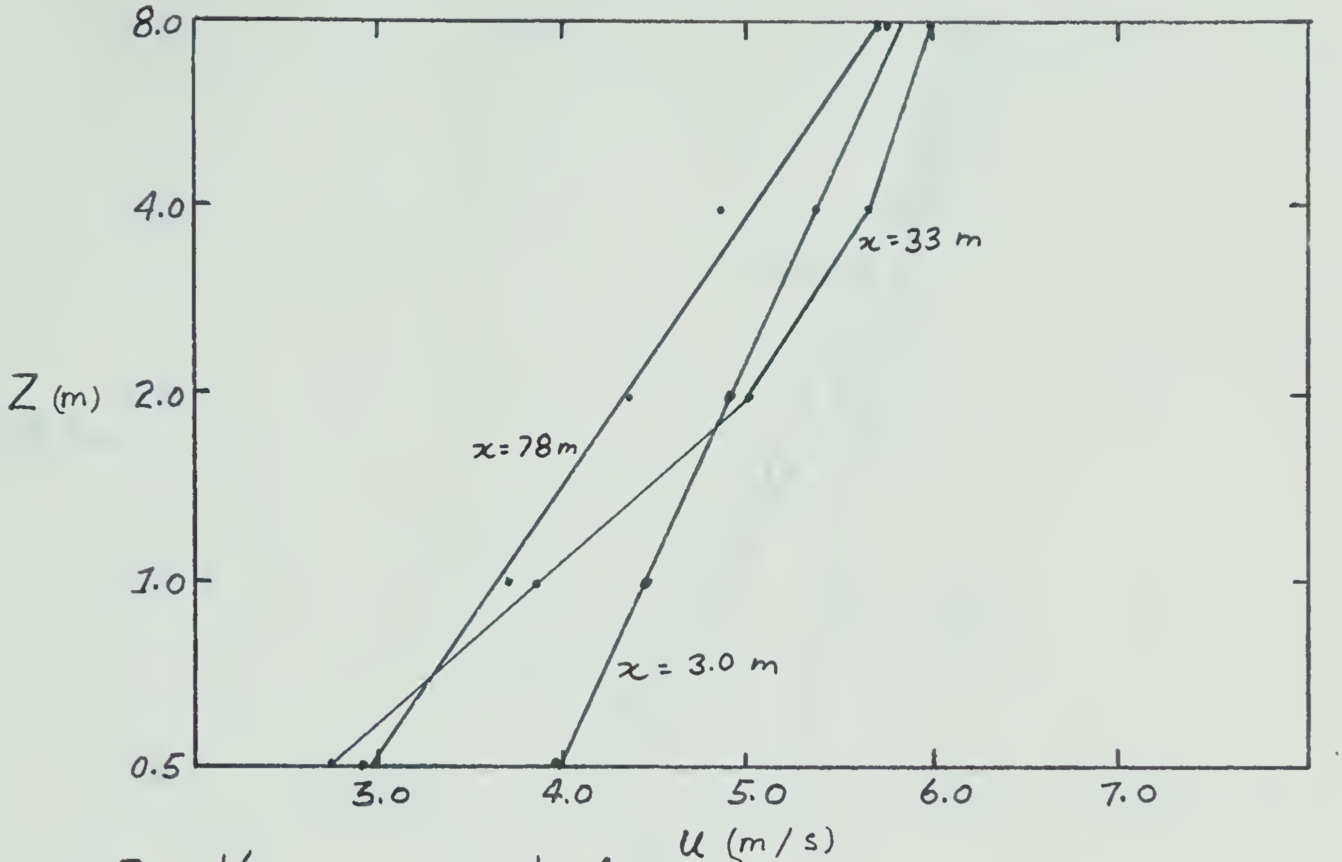


Fig 16 Trial 4

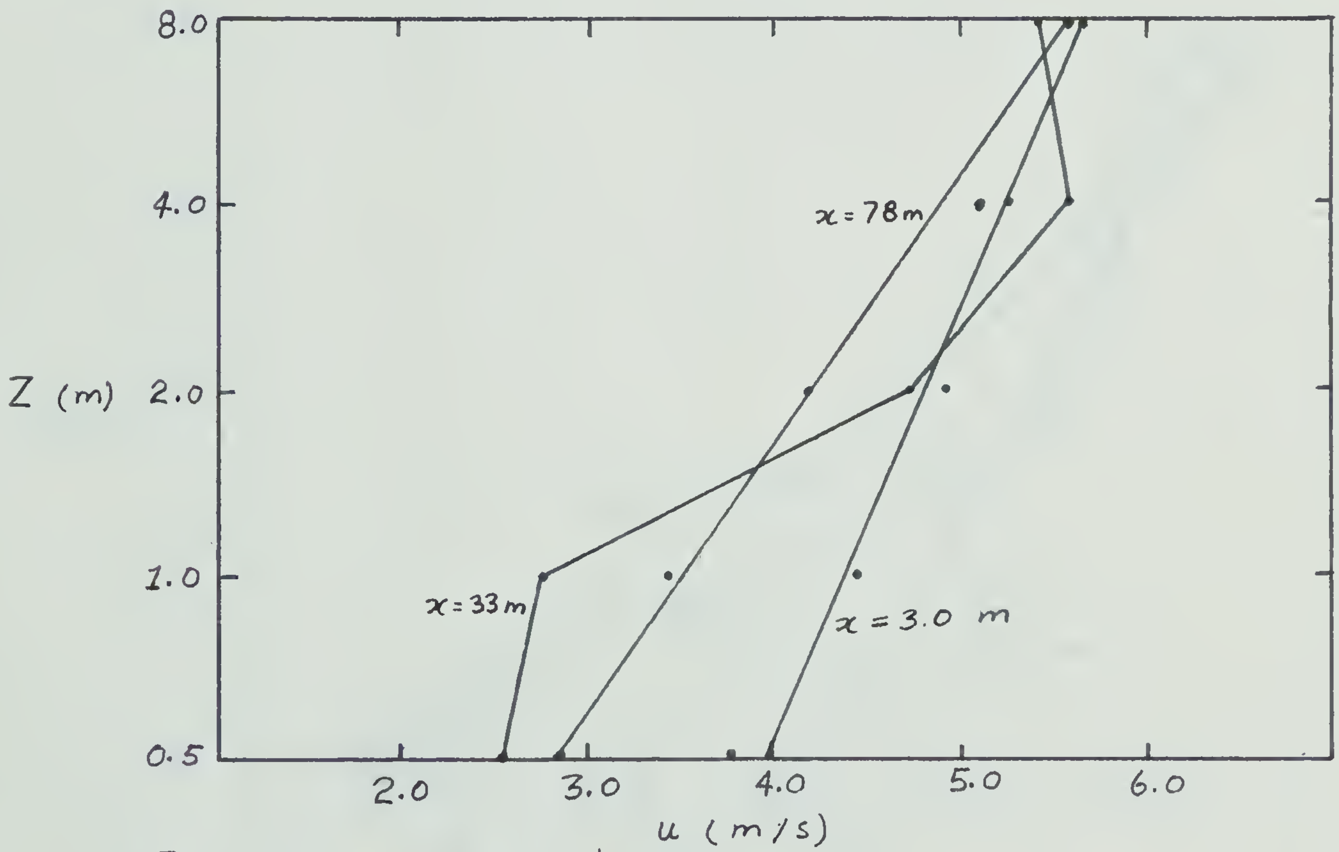


Fig 17 Trial 5

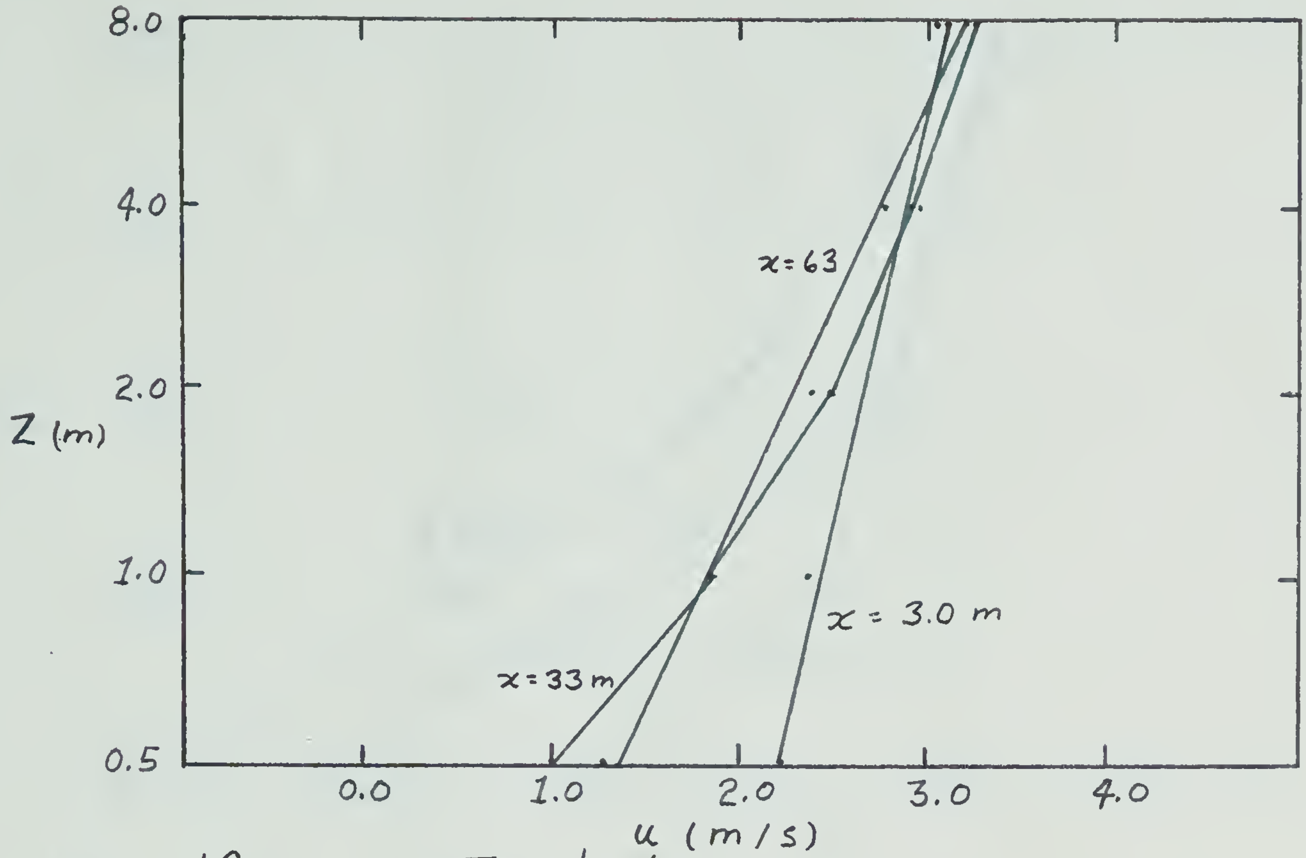


Fig. 18 Trial 6

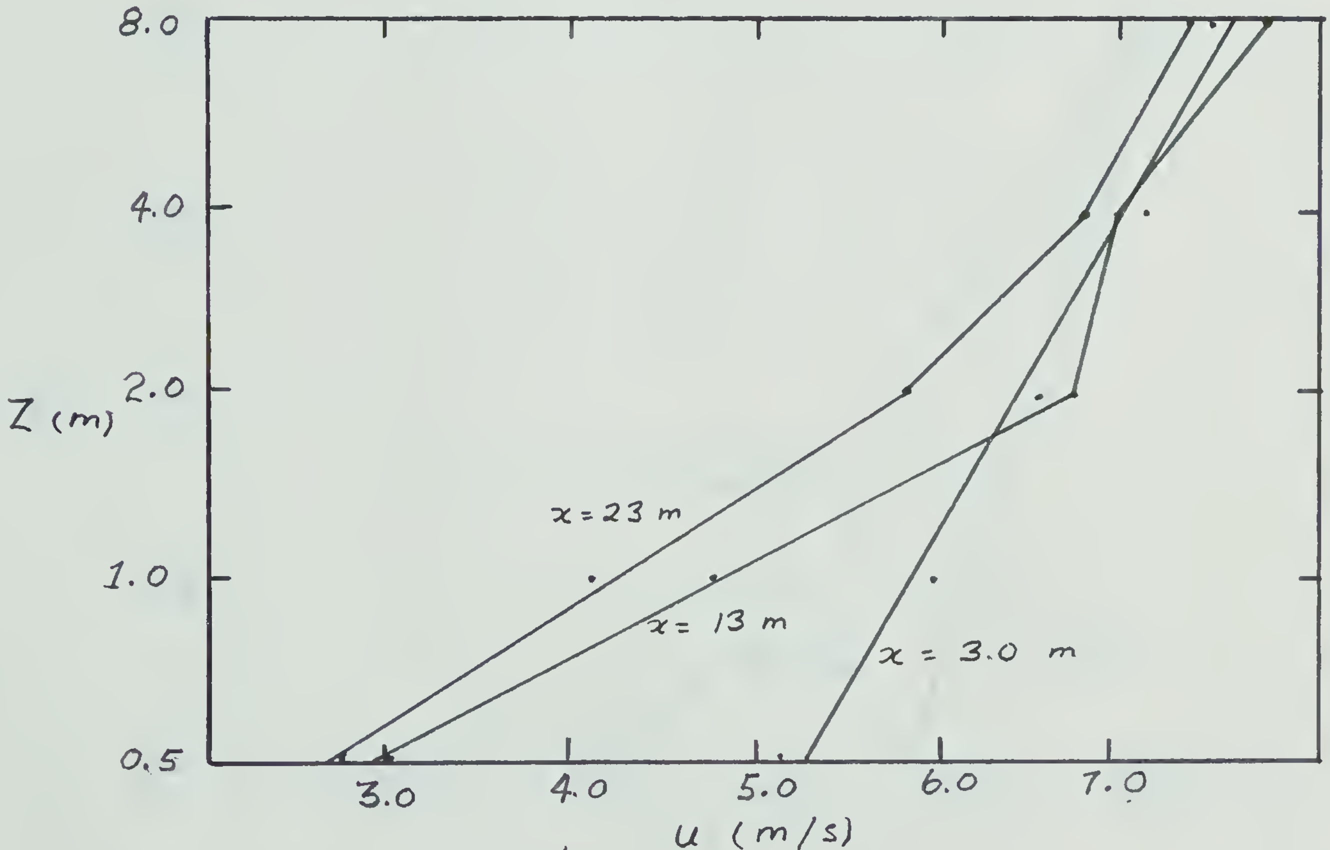
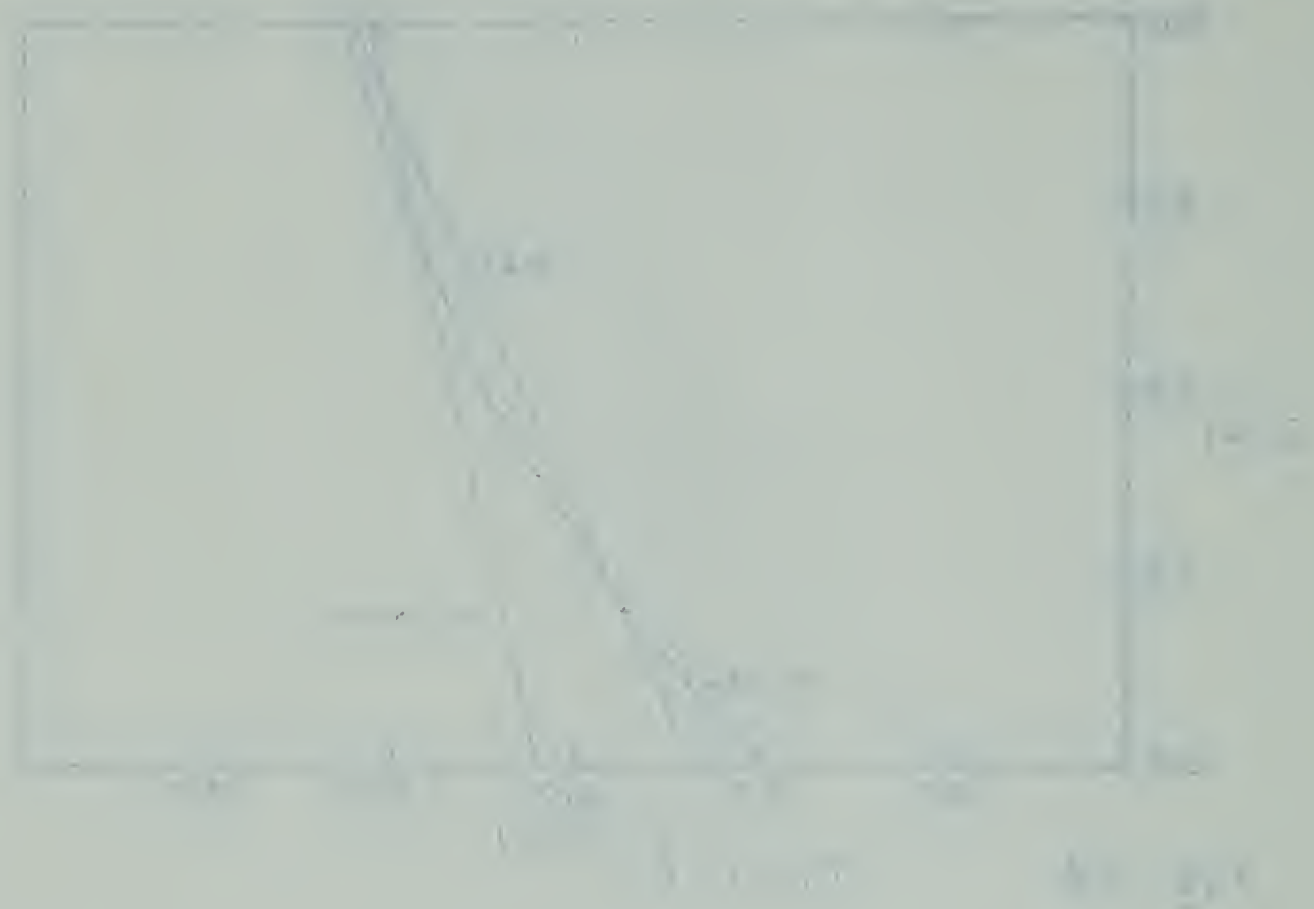
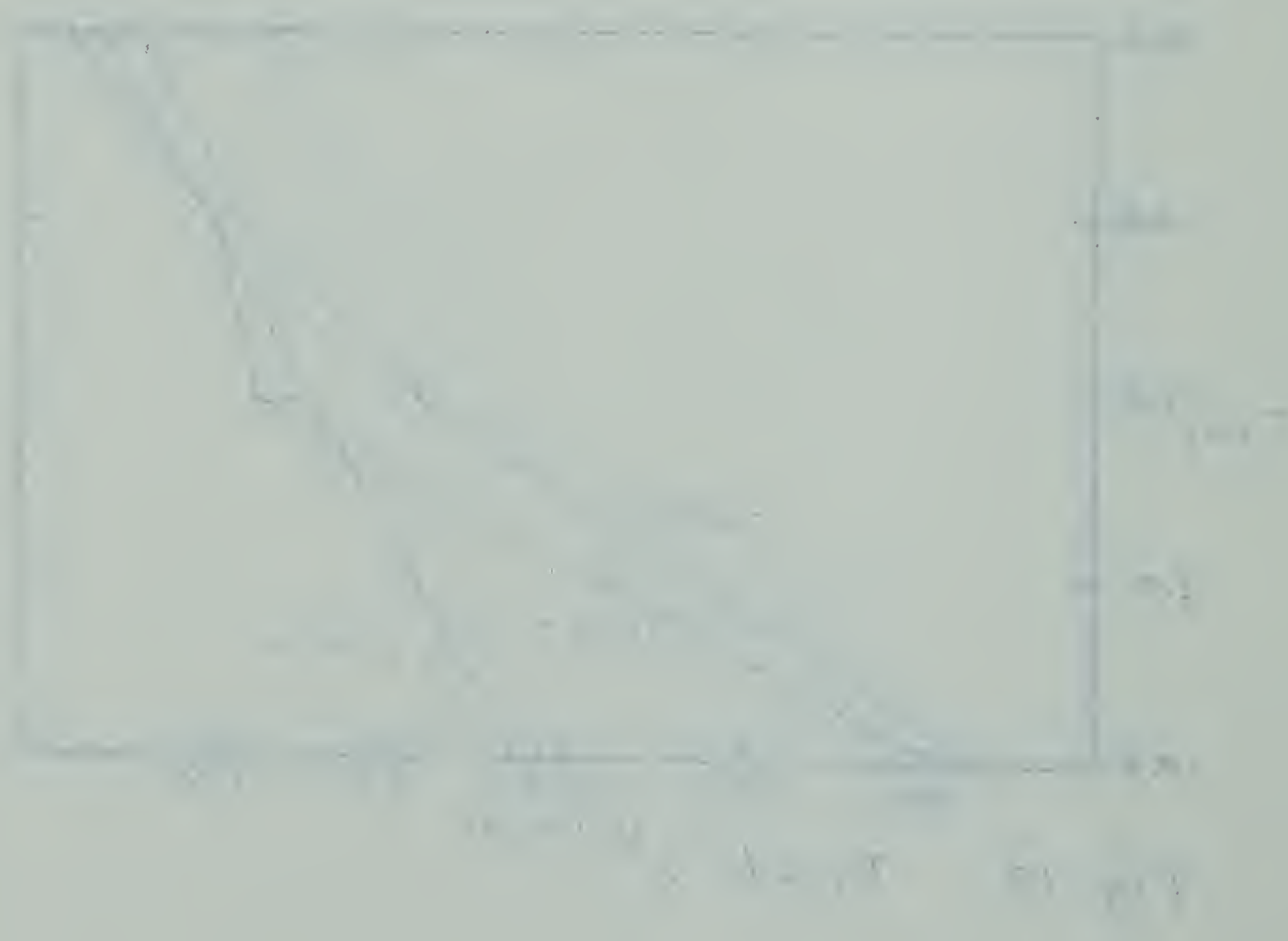


Fig 19 Trial 7





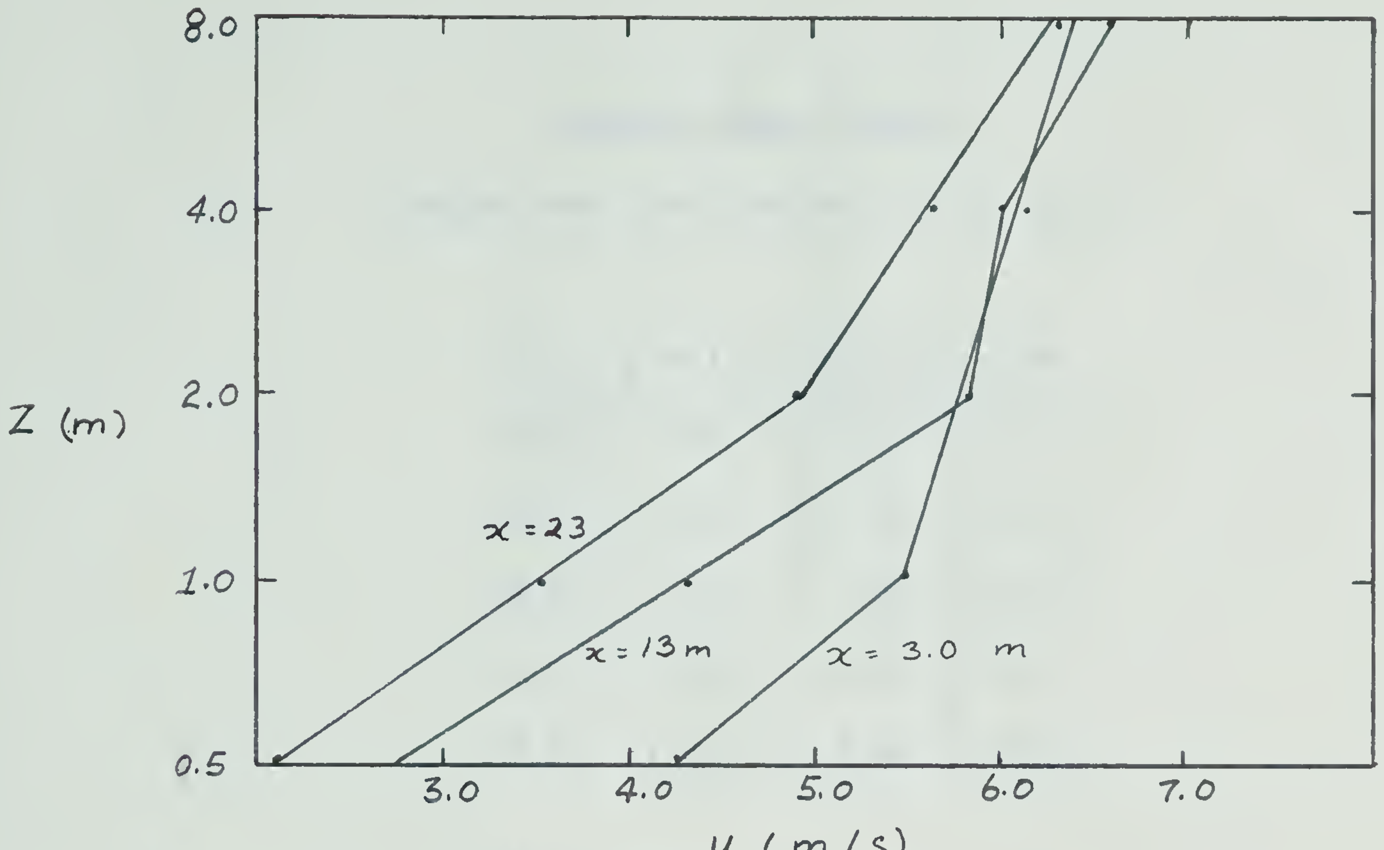


Fig 20 Trial 8

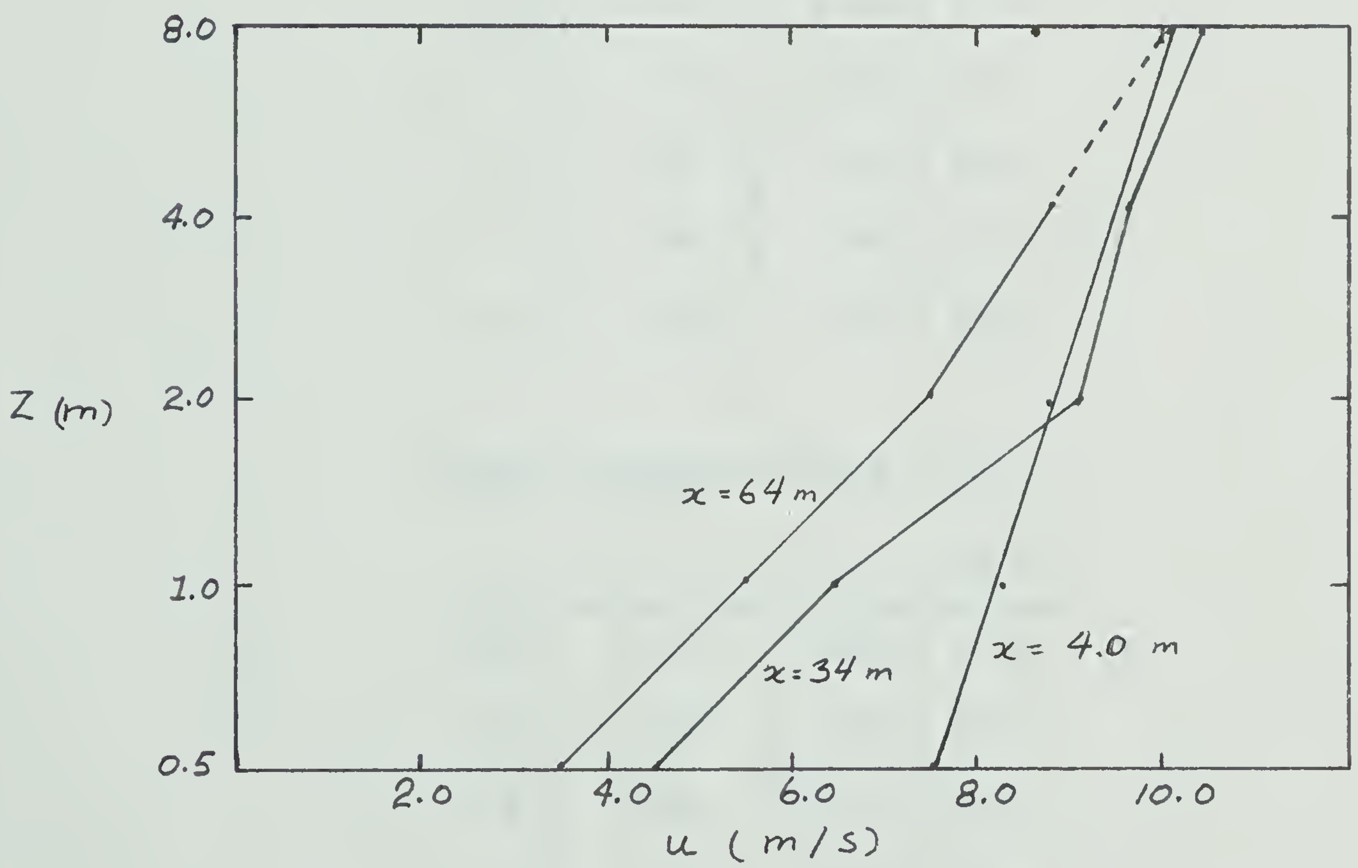
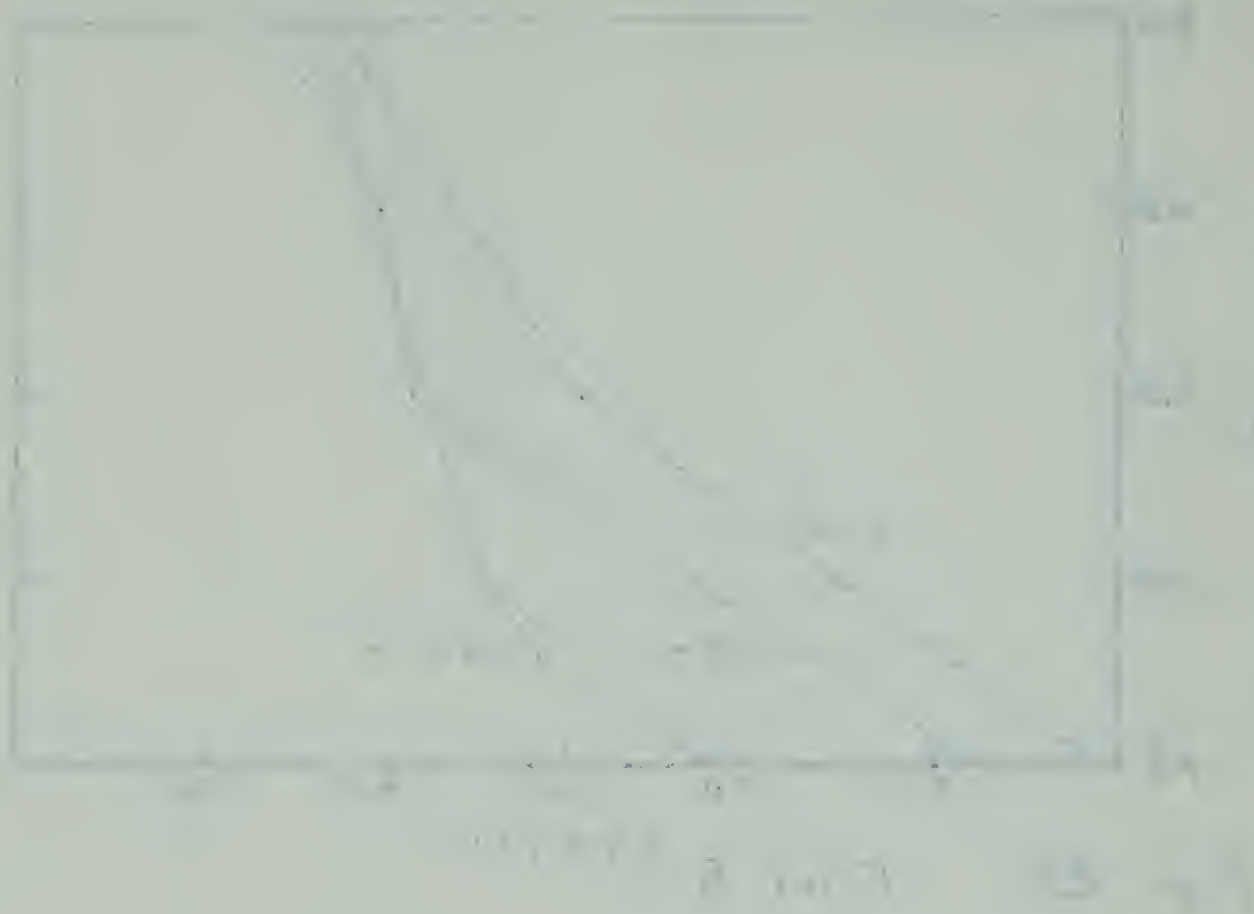


Fig 21 Trial 9



OVERALL MEAN PROFILE

(using data from Trials 1, 4, 5, 6, 9)

z \	x = 3.0	33.0	69
8.0	5.55	5.62	5.21
4.0	5.22	5.33	4.92
2.0	4.76	4.76	4.15
1.0	4.42	3.41	3.28
0.5	3.91	2.45	2.40

MEAN OF "NEUTRAL" TRIALS (5,9)

z \	x = 3.5	33.5	71
8.0	8.42	8.44	7.57
4.0	7.95	8.08	7.51
2.0	7.31	7.34	6.21
1.0	6.80	4.89	4.75
0.5	6.02	3.74	3.39

MEAN OF UNSTABLE TRIALS (1,4,6)

z \	x = 3.0	33.0	68.0
8.0	4.25	4.38	4.22
4.0	3.99	4.10	3.74
2.0	3.59	3.57	3.24
1.0	3.32	2.80	2.66
0.5	2.94	1.87	2.02

MEAN OF TRIALS 7 AND 8

z \ x =	3	13	23
8.0	6.81	7.18	6.79
4.0	6.61	6.50	6.20
2.0	6.19	6.26	5.35
1.0	5.70	4.54	3.82
0.5	4.71	2.85	2.25